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SCIENCE FOR DISASTER RISK MANAGEMENT 2017

Knowing better and losing less

Disaster
Risk
Management
Knowledge
Centre

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SCIENCE FOR DISASTER RISK MANAGEMENT 2017
Knowing better and losing less

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FOREWORD

Dear policymakers, practitioners or scientists,

It is deeply encouraging to see how quickly the scientific community has mobilized to play its full part in implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030 with the overall aim of reducing disaster risks and losses, and shifting the emphasis from managing disasters to managing the underlying risks.

The Sendai Framework clearly recognises the strong role that the scientific community can play in improved understanding of risk and communicating on new knowledge and innovation. The European Commission took the initiative early by launching the Disaster Risk Management Knowledge Centre in September 2015, just six months after the adoption of the Sendai Framework as a contribution to the Science and Technology Roadmap. Now we have this insightful publication as the first fruit of its labours.

The UN Office for Disaster Risk Reduction (UNISDR) and European Commission, Joint Research Centre (JRC) have been partners to stimulate new research and to encourage the use of available science by all stakeholders.

JRC was one of the co-organisers of the UNISDR Science and Technology Conference in January 2016, which produced an ambitious Science and Technology Roadmap and launched the Science and Technology Partnership.

The JRC has worked with over 200 top scientists, practitioners and policy makers from many fields to summarise the state of the science relevant to disaster risk management, and to make it accessible in this current report. The aim is to break out of the silos, demystify work from other disciplines, encourage potential synergies across disciplines, and to identify gaps in scientific knowledge for future research.

This report summarises the state of relevant science from a European perspective. We consider it as the start of a continuing process, the beginning of a wider, worldwide partnership to summarise knowledge globally, and make it available to the disaster risk management community.

The report is timely for the discussions at the Global Platform for Disaster Risk Reduction in Mexico in May 2017. It caters for the need to translate the wealth of available science into language understandable by stakeholders such as policy makers, practitioners and scientists from other disciplines.

We invite you to engage with us, now and in the future, to enhance the science-policy interface so that strategies for disaster risk reduction at national and local level, which will be put in place by the Sendai Framework deadline of 2020, are based on sound evidence and robust science.

Robert Glasser,
United Nations Special Representative
of the Secretary-General for Disaster Risk Reduction

Vladimir Šucha,
Director General,
European Commission, Joint Research Centre

PREFACE

The Disaster Risk Management Knowledge Centre has produced this flagship science report as a contribution to the Science and Technology Roadmap of the Sendai Framework for Disaster Risk Reduction.

This report is the result of the multi-sectorial and multi-disciplinary networking process and represents the combined effort of more than two hundred experts.

It will support the integration of science into informed decision making through synthesizing and translating evidence for disaster risk management and strengthening the science-policy and science-operation interface.

EXPECTATIONS

This report aims to provide reviews of scientific solutions and their practical use in various areas of DRM in Europe. It is comprehensive in scope but selective in topic and is written in a format that is intended to be accessible to all DRM actors. The reviews of the scientific evidence base are summaries of (1) recent advances/outcomes of EU research projects, (2) relevant national work and (3) relevant international work.

The report aims to bridge science and policy as well as operation communities. The intended audience consists of practitioners and policy makers in addition to experts from different scientific disciplines. It seeks to understand the scientific issues of relevance to their work; specifically civil protection operations and disaster risk policy, but equally climate adaptation policy. The audience includes government officials at EU, national, regional and local levels interested in finding better ways to use science, and also scientists to help them understand work in other disciplines that would allow the identification of possible cross-sectoral synergies and needs from practitioners.

THE PROCESS

The Disaster Risk Management Knowledge Centre has committed to producing a series of reports to analyse, update the state of the art and identify research and innovation gaps in the field of DRM. Each report will be multi-hazard, multi-disciplinary, and will address the full disaster risk cycle; it will have scientific-oriented contributions presenting the state of science, and practitioner-oriented contributions presenting the use of science.

The process started in January 2016, when the DRMKC working group defined expectations and developed the outline of this report, the first in the series. The process was run by the JRC Editorial Board of 4 members with strong support from the European Commission Advisory group of 79 experts in specific topics. The writing phase was carried out by Author teams consisting in total of 8 Coordinating Lead Authors, 3 Facilitators, 34 Lead Authors and 140 Contributing Authors. The drafts were circulated for formal review to 123 scientific experts, policymakers and practitioners. The preparation of the report succeeded in pulling together a network of 273 contributors from 26 mostly European countries and 172 organizations. It has been endorsed by 11 European Commission Services and will be officially released at the Global Platform for Disaster Risk Reduction in May 2017.

STRUCTURE

Understanding disaster risk to manage it is one of the main focus of Sendai Framework. This perspective already opens two big issues: understanding disaster risk with the focus on scientific evidence, and managing disaster risk with the focus on knowledge applied by different actors. In order to convey the DRMKC's mission of bridging science and the policy/operation community, the issue of communicating disaster risk has been introduced with a

The "Bridge concept"

strong focus on how to successfully overcome barriers to implementing knowledge in the field of DRM.

The scope of the report is divided conceptually into three distinct parts: understanding disaster risk, communicating disaster risk and managing disaster risk, forming the "bridge concept" of the report.

The "Understanding disaster risk" part has been split into two chapters: Chapter 2, covering risk assessment methodology and examples in general, and Chapter 3 that provides a comprehensive overview of hazard related risk issues, the structure of which follows the Sendai taxonomy of hazard classification. Chapter 4 on "Communicating disaster risk" tackles many issues on communication in different phases of DRM among different actors. Chapter 5 "Managing disaster risk" addresses the governance issues of the full disaster risk cycle.

The first and last chapter wrap the scope of the report into a whole. Chapter 1 "Current status of disaster risk management and policy framework" aims to explain why recent global and European initiatives are beginning to seek help to strengthen society's resilience by using science and technology. The final Chapter 6 "Future challenges of disaster risk management" aims to inform decision makers and practitioners of existing science that should find its way into legislative form and practice as well as tackling a much more challenging purpose: to recognise knowledge gaps that could serve as valuable reference based input for a Horizon2020 call.

ACKNOWLEDGEMENTS

We wish to express special thanks to all the Coordinating Lead Authors, Lead Authors, Contributing Authors, Reviewers and EC Advisors. Without their expertise, experiences and a huge commitment to a cause, this report with such a holistic understanding of both disaster risk and disaster risk management could never have been completed.

It is our pleasure to invite you to explore the content of this report and we wish you pleasant and informative reading.

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Disaster Risk Management Knowledge Centre

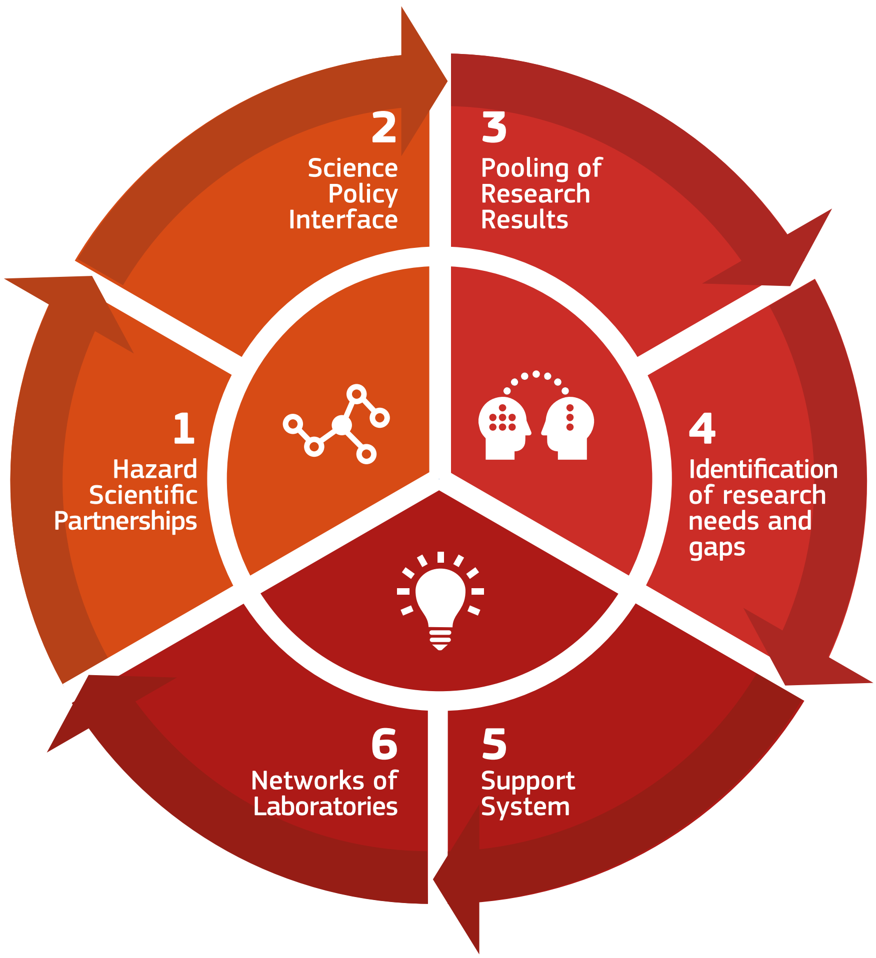
Enhancing the Knowledge base to support Disaster Risk Management

Faced with the risk of increasingly severe and frequent natural and man-made disasters, policy-makers and risk managers in Disaster Risk Management (DRM) and across EU policies increasingly rely on the wealth of existing knowledge and evidence at all levels – local, national, European and global – and at all stages of the DRM cycle – prevention; reduction; preparedness; response and recovery.

Better knowledge, stronger evidence and a greater focus on transformative processes and innovation are essential to improve our understanding of disaster risk, to build resilience and risk-informed approaches to policy-making, and contribute to smart, sustainable and inclusive growth.

The Disaster Risk Management Knowledge Centre (DRMKC) provides a networked approach to the science-policy interface in DRM, across the Commission, EU Member States and the DRM community within and beyond the EU. This Commission initiative builds on three main pillars:

Partnerships and networks to improve science-based services;
Better use and uptake of research and operational knowledge;
Innovative tools and practices for risk and crisis management;



Activities of the DRMKC support the translation of complex scientific data and analyses into usable information and provides science-based advice for DRM policies, as well as timely and reliable scientific-based analyses for emergency preparedness and coordinated response activities. It brings together existing initiatives in which science and innovative practices contribute to the management of disaster risks.

At a global level, the EU supports the Sendai Framework for Disaster Risk Reduction to promote a more systematic and reinforced science-policy interface to strengthen the contribution of DRM to smart, sustainable and inclusive growth globally.

In practice:

Partnership

To achieve the ambitious goal of fully exploiting and translating complex science into useful policy and applications in DRM, the DRMKC reinforces the development of disaster science partnerships and networks.

- ***Where knowledge begins***: Networks and activities are activated and promoted to improve the science-policy interface in prevention activities and to facilitate the translation of complex science into useful policy advice.

- ***Where knowledge applies***: Partnerships for operational preparedness and response to major natural disaster types in the EU are promoted to facilitate the information flow between the different partnerships, the Emergency Response Coordination Centre (ERCC) and Member States.

Knowledge

Scientific research results and operational knowledge gained from lessons learnt, exercises, training, peer reviews and other assessment tools need to be better exploited in the DRM cycle to mitigate risks and vulnerabilities and to improve response when disaster strikes.

- ***Where knowledge meets***: A common repository of relevant research and operational projects and results will be accessible through the DRMKC and its Web-platform.

- ***Where needs are identified***: A science advisory panel of experts and scientists at local, national and European levels provides analyses, updates and advice into research and innovation needs in DRM.

Innovation

Industry and the scientific community play an essential role in developing innovative methods, tools and technological solutions for the mitigation of disasters and their impacts. They facilitate the work of first responders and other operational actors in crisis management through innovative technologies and instruments.

- ***Where gaps are filled***: A Support System facilitates the use of existing expertise to help Member States meet risk management related obligations – DRM Capabilities Assessment, Disaster Loss Databases, Science-policy interfaces, National Risk Assessment.

- ***Where innovation is tested***: The DMKC assesses the current state of DRM science and technology in Europe and addresses technological and operational challenges to cover the existing gaps, and assists in building globally common standards, through the European Network for Innovation Test Beds (ENITB) and the European Crisis Management Laboratory (ECML).

The DRMKC is supported and coordinated by a number of Commission Services in partnership with a key network of Member States. A Steering Committee meets regularly to propose, discuss and establish the activities and priorities of the knowledge centre.

The DRMKC web-platform facilitates information and knowledge sharing, while enhancing the connection between science, operational activities and policy: http://drmkc.jrc.ec.europa.eu/

SHORT EXECUTIVE SUMMARY

Knowing better and losing less

Natural and human-induced disasters present major risks to the economy, the security and well-being of citizens and society. Addressing these risks relies on robust evidence-based decision-making. A main challenge for policy-makers and practitioners addressing natural and human-induced disaster risk management, across all policies and sectors, is to capitalise on the wealth of existing knowledge at all levels – local, national, European and global.

Science and technology play a central role in many EU policies and international agreements addressing disaster risk management. Ensuring efficient disaster risk reduction and prevention measures relies on a robust understanding and assessment of risks.

The UN Sendai Framework for Disaster Risk Reduction calls for a strong interface between science and policy to build a strong knowledge of disaster risk; make efficient use of data to better understand the economic impacts of disasters; and develop adequate preventive policies to reduce the risks of disasters. Science and innovation equally contribute to several Sustainable Development Goals and their associated targets. In the context of the Paris Agreement on climate change, the importance of data collection, evidence-based approaches and the contribution of science was recognised.

This report presents a synthesis of scientific knowledge in the field of disaster risk reduction. It draws from many scientific disciplines, practitioner communities and policy experts. It is organised in 6 parts. Chapter 1 summarises the policy landscape. Chapters 2 and 3 present the available knowledge on risk assessment respectively from a multi-hazard and hazard specific perspective. Chapter 5 discusses science for managing disaster risk, and Chapter 4 bridges science and practice by focusing on communication of risk. Finally, Chapter 6 summarises challenges brought forward by all authors.

Current status of disaster risk management and policy frameworks

A main challenge for policymakers addressing natural and human-induced disaster risk management, across all EU policies, is to capitalise on the wealth of existing knowledge at all levels — local, national, European and global. In order to improve all stages of the disaster risk management cycle — prevention and mitigation, preparedness, response and recovery —, the knowledge and evidence base needs to be further improved, advances in relevant technology exploited, research results applied and the interaction between researchers and end users enhanced. Understanding the state of play of policy frameworks relevant to disaster risk management will help strengthen the interface between science and policy required to reduce the risk of disasters and enhance our prevention and mitigation, preparedness, response and recovery.

Understanding disaster risk: risk assessment methodologies and examples

Risk is complex. There have been huge advances in recent years in all of the key areas of risk: hazard, exposure and vulnerability. The science base in Europe is a rich source of information and data. Initially there was often a culture clash between the needs of industry for practical useable information within tight timetables, perhaps just representing what is known, compared to academia's focus on research and discovery with necessarily longer time horizons. With greater exposure and encouragement, including EU research grants promoting partnerships between the public and private sectors and academia, scientists and practitioners are now more attuned to working closely with each other. Similarly, methodologies have now been developed to categorise risk, model risk and present the results of risk assessments and analysis in forms that enable decision makers not only to decide the right course of action but also to provide transparency around the decision-making process.

The process of risk understanding is not simple and data are always partial and flawed. Initial models and analysis may be viewed as simplistic, particularly in retrospect. The discrepancies in data quality are sometimes asserted an excuse to delay risk analysis and modelling, but it is infinitely better to embark on a risk assessment and analysis process from the outset than wait until better data become available. A "1 in 100 event" could happen tomorrow, it is better to have tried, and commit resources to develop a greater understanding of the risks as far as possible now (and so identify key weaknesses and data gaps) than postpone action until better data are collected.

Risk assessments and risk models cannot make decisions but they can inform policy. Policymakers may reject the advice of a risk model but if they do so, they should be able to articulate why. In practice no model includes all factors; decisions based upon broader considerations are often valid. But there is no doubt that encouraging and developing a culture of risk identification, risk understanding, risk assessment and risk modelling ultimately benefits society, making it more resilient and saving lives, livelihoods and property.

Understanding disaster risk: hazard related risk issues

Today monitoring of geophysical phenomena is performed with well-developed instrumental recording networks extended at global, regional, national and local levels. However, since large geophysical events tend to occur infrequently and may appear benign for generations, the risks may be underestimated. The assessment of risks posed by earthquakes, volcanic eruptions and tsunamis first requires a good knowledge of the type, magnitude and frequency of past events. The preparation of hazard maps is a good practice not only for decision makers but also for citizens who would like to know where the hazardous areas are situated and what types of hazards threaten their community.

There is important room for further improvement of monitoring systems and their geographic expansion in less well covered areas. If appropriate monitoring is in place, it may be possible to issue early warnings for different hazards and to provide short term forecasts of likely future activity. The assessment of event scenarios can play a critical role in the development of risk management and risk reduction measures, such as elaboration of emergency plans, development of infrastructure to support the affected regions, or risk awareness campaigns.

Developing adequate hydrological risk maps is key for the short term (emergency response) as well as the long term planning (urban and rural development) to increase society's resilience to those risks. Fully comprehensive hydrological risk maps require a great deal of data including long time series of events, and/or a chain of models and assessments that reflect our level of understanding of the complex physical processes controlling hydrological events.

Different types of floods are predictable with different time ranges. Flash floods driven by convective rainfall are notoriously challenging to predict ahead in time to produce effective early warnings, whereas slower developing floods in large catchments can be predicted several days ahead with the use of probabilistic flood forecasting systems. Landslides mapping is a challenge due to the extraordinary breadth of the spectrum of landslide phenomena. No single method exists to identify and map landslides and to ascertain landslide susceptibility and hazard.

The majority of recent scientific studies indicate that hydrological risks will increase overall even for warming levels of 1.5°C. It is estimated that about 70% of the global coastlines are projected to experience a sea-level change within 20% of the global mean sea-level change.

Meteorological risks include hazards from different types of storm systems as well as extremes of temperature, climatological risks include droughts and wildfires and biological risks include epidemics and pandemics. In order to mitigate the effects of these hazards, an understanding of their origin, behaviour and evolution is critical. Building knowledge about human vulnerability to the various hazards is required, and region-specific hazard, exposure and vulnerability need to be analysed for different sectors.

Forecasting the onset or likely evolution of hazards is becoming more accurate through the use of new technologies; however there remains a degree of uncertainty which can be problematic for decision-makers as it can be difficult to strike the right balance between the risk of missing the opportunity for early warning and the risk of raising too many false alarms. Improvements in forecasting will be driven by the interaction and partnerships forged between different fields.

Disaster risk reduction frameworks have not commonly addressed technological risks. The Sendai Framework for Action recognises the importance of technological hazards and promotes an all-hazards approach to disaster risk reduction. This includes hazardous situations arising from man-made activities due to human error, mechanical failure, and natural hazards.

Chemical accidents continue to occur relatively frequently in industrialized and developing countries alike, which raises questions as to the adequacy of current risk-reduction efforts. The causes underlying chemical accidents in current times are largely assumed to be systemic. Most chemical accidents today are caused by violations of well-known principles for chemicals risk management which has led to insufficient control measures. Natech accidents are a technological "secondary effect" of natural hazards and have caused many major and long-term social, environmental and economic impacts. Studies on the status of Natech risk management in the EU and the OECD have highlighted deficiencies in existing safety legislation and the need to consider this risk more explicitly. Conventional technological risk-assessment methodologies need to be expanded to be applicable to Natech risk assessment and only a very few methodologies and tools are available for this purpose.

Communicating disaster risk

Disaster risk communication is a growing field in disaster science, and highly relevant for policy makers, practitioners and citizens. It aims to prevent and mitigate harm, prepare populations of vulnerable areas before a disaster strikes; and to validate, share, disseminate and combine information from various sources both at times of disasters and in the recovery phase.

There is not a one size fits all in risk communication, as the local context (e.g. local cultures) and histories (e.g. previous experiences with disasters) matter. Risk communication based on a one-way approach that tells people how to prepare and to respond to a disaster is rarely effective. Instead, a two-way mode of communication will lead to a situation in which people become more engaged in risk communication. This engagement increases the likelihood that someone can successfully cope with a situation of uncertainty.

The key challenges in risk communication lie not so much in developing new tools and innovations but in the implementation of social mechanisms by which such innovations become embedded in actual communication practices. Adequate disaster risk communication and management requires the collaboration of a variety of stakeholders including policy makers, practitioners and citizens.

Managing disaster risk

The disaster management cycle commonly includes four types of measures needed to manage disasters: prevention/mitigation and preparedness (before a disaster), and response and recovery (after disaster). Holistic understanding of disaster risk management focuses on all four phases of the disaster cycle.

Based on an analysis of the benefits arising from avoided losses, mitigation and prevention measures are widely considered more cost-effective than ex-post disaster interventions. An increase in mitigation investment has occurred in some European countries, but the lack of public and therefore political interest in prevention and mitigation remains a problem.

In disaster preparedness and response planning there is a trend towards greater professionalization of emergency management across all Europe supported by evolution of legislative and regulatory frameworks. A comprehensive strategy for disaster financing can moderate the impacts of natural hazard risks, speed up recovery and reconstruction, and harness knowledge and incentives for risk reduction. The private financial sector plays an important role, along with governments and civil society organizations, in designing innovative financial protection goals and sharing knowledge and capacity.

Public-private partnerships are a model for a joint bearing of responsibilities and efficient risk-sharing, capable of increasing insurance coverage and penetration, and guaranteeing a strong financial backing in view of uncertain probabilities of risk.

Future challenges of disaster risk management

Drawing from the analysis in each chapter, the report concludes with a summary of challenges for knowledge, partnerships and innovation addressed to the three reader communities: scientists, policymakers and practitioners.

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Chapter 1

Current status of disaster risk management and policy frameworks

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1 Current status of disaster risk management and policy frameworks

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CONTENTS

1.1 Introduction

Since 1990, over 1.6 million people have died in reported disasters around the world. Despite important improvements in the management of disasters, economic losses remain at an annual average of EUR 235 billion (USD 250 billion) to EUR 280 billion (USD 300 billion) (UNISDR, 2015). The European Union is not spared, as disasters have caused over 90 000 deaths and EUR 100 billion in economic loss since 2000 (CRED, 2017).

The impacts of disasters have significantly increased in recent years, partly as a result of climate change, rapid and unplanned urbanisation, population growth and environmental degradation (European Commission 2014). No country alone can be fully prepared for all kinds of disasters. We need to act together and benefit from a coordinated common response and to be stronger and more efficient.

Policymakers and risk managers in disaster risk management (DRM) and across EU policies increasingly rely on the wealth of existing knowledge and evidence at all levels — local, national, European and global — and at all stages of the DRM cycle — prevention and mitigation, preparedness, response and recovery. Innovative ways to carry out DRM policies and operations are necessary. In this respect, the European Commission itself recognises that 'the challenges faced by the EU today require fast and effective solutions from the Commission, which often involve multiple policy areas' (European Commission, 2016a). The 2015 United Nations World Conference on Disaster Risk Reduction and its associated Sendai framework 2015-2030 (UNGA, 2015a) is an ambitious appeal for cooperation and actions to achieve substantial results at the global level. The European Commission has been instrumental in contributing to a better understanding of disaster risk in all its dimensions and defines its priorities for actions under a comprehensive Sendai action plan (European Commission, 2016b).

Natural and man-made disasters present major risks to the economy, security and well-being of citizens and society. Addressing these risks relies on robust evidence-based decision-making.

Over the years, the EU and its Member States have developed substantial experience in enhancing and mainstreaming DRM across a range of policies at national, European and global levels.

This chapter sets the policy scene for this report by highlighting some of the main policy processes and instruments at European and global levels, which contribute to the management and the reduction of disaster risks. It provides examples of how science and knowledge contribute to DRM in policy areas such as civil protection, humanitarian aid, climate change adaptation, flood risk management, earth observation, critical infrastructure protection, regional policy, health and research and innovation policies. In doing so, this chapter underlines the extent to which strengthening the contribution of science throughout these policy areas is an important step towards reducing disaster risks through robust evidence-based decision-making.

1.2 Disaster prevention and risk reduction through risk-informed policies

In the area of disaster management, the recent Union Civil Protection Mechanism (UCPM) addresses disaster risks both in the EU and in third countries by strengthening cooperation and facilitating coordination within Europe in the areas of disaster prevention, preparedness and response (European Union, 2013a). The European Commission and its Member States work to strengthen the EU's resilience to crises and disasters through the development and use of scientific tools in crisis management, satellite image processing and analysis, DRM surveillance systems and other forms of integrated systems for risk management, situational awareness, early warning and collaborative decision-making.

The area of disaster prevention is recognised under the UCPM to be a key component to protect and build resilience to disasters, as a first and vital stage in the full DRM cycle. Ensuring the prevention and reduction of disaster risks relies on a robust knowledge base on disaster risks and efficient sharing of knowledge, best practices and information. Strong knowledge on disaster risks and the contribution of science are important for Member States to undertake risk assessments, assess risk management capabilities and record loss and damage data on disasters. The European Commission also relies on robust knowledge and evidence to support Member States in reinforcing their prevention capacities and actions, as illustrated in Box 1.1 (European Union, 2013a).

In humanitarian policy, the EU is one of the major donors in terms of meeting response needs and reducing the risks of disasters worldwide (European Community, 1996). It relies on a strong knowledge and evidence base as well as on a growing culture of innovation. In this context, the European Commission is playing a central role to develop and promote the INFORM index for risk management, which is a global, open-source risk assessment for humanitarian crises and disasters, contributing to global efforts to reinforce risk assessments and risk reduction strategies — see Box 1.2.

Disaster prevention and risk reduction are cross-cutting to a number of key EU policies. Ensuring efficient disaster risk reduction and prevention measures relies on a robust understanding and assessment of risks.

Science also plays an important role in enhancing the resilience and performance of vital and critical infrastructures and services. In the case of the European programme for critical infrastructure protection (European Commission, 2006), several research projects have been financed to develop fresh knowledge and innovative concepts in this area. This has led to progress in the development of risk assessment methodologies and other tools for critical infrastructure protection, in the analysis of interdependencies and cascading effects and in responses to man-made threats and natural hazards. The programme has led to a better understanding of the issues related to critical infrastructure protection and has helped Member States develop their own national strategies and research projects.

Disaster risk reduction (DRR) and climate change adaptation are intrinsically linked in reducing risks and vulnerabilities to climate-related hazards. Both rely on the availability of robust knowledge and data at all levels. Knowledge and data are key in defining scenarios and projections according to which adaptation measures are developed, in monitoring progress of implementation and in developing innovative instruments/tools to increase resilience. The development of appropriate methodologies and the sharing of good practices are key in carrying out national risk assessments and the assessment of risk management capabilities. Improving the recording of loss and damage data relies on robust systems, models and methodologies. Science will help improve the understanding of risks and the undertaking of the vital first steps to-

BOX 1.1

EU Overview of natural and man-made disaster risks

The European Commission is mandated under the UCPM to develop a comprehensive overview and mapping of natural and human-induced disaster risks in the EU as one of its key disaster prevention actions (Article 5.1(a), ibid.). The overview, published in 2017 and to be updated on a regular basis, builds on national assessments of disaster risks and extensive scientific input (European Commission, 2017).

Science plays a central role in developing a comprehensive understanding of disaster risks across Europe, with a particular emphasis on cross-border, emerging and new risks and taking into consideration climate change.

wards DRM and adaptation planning. The global threat of new and re-emerging infectious diseases and man-made and natural disasters requires reinforcing the infrastructure of public health response through strengthening health systems and the global health security framework. The EU decision on serious cross-border threats to health (European Union, 2013b) provides the framework to improve prevention and preparedness and to strengthen the capacity to coordinate response to health emergencies across the EU; emergencies caused by biological, chemical and environmental agents and threats of unknown origin aiming to contribute to a high level of public health protection The EU health programme provides scientific support and capacity building in Member States through training and exercises, sharing experiences, guidelines and procedures, and technical support and expertise with preparedness planning or for implementation of improvements in certain areas such as maritime traffic or specialised laboratories. In the field of emerging and re-emerging infectious diseases, science and innovation play a key role in vaccine, diagnostics and drug development and in risk modelling and assessment, as well as in identifying effective prevention and control strategies at the population level. The EU Early Warning and Response System is instrumental in notifying alerts as well as measures undertaken by the Member States.

Major industrial accidents can have consequences beyond the limits of industrial establishments and the human, ecological and economic costs of an accident are borne not only by the establishment affected, but also by the society concerned. It is therefore necessary to establish and apply safety and risk reduction measures to prevent possible accidents, to reduce the risks of accidents occurring and to minimise the effects if they do occur, thereby making it possible to ensure a high level of protection throughout the Union. The Directive 2012/18/EU on major-accidents hazards involving dangerous substances (European Union, 2012), also known as 'Seveso III', sets risk management goal-oriented objectives based on the fact that operators are obliged to take all necessary measures to prevent major accidents and to limit their consequences for human health or the environment. The directive is focused on the unintentional (accidental, including natural hazards) potential events in the establishments, thus usually not related to the intentional acts (attacks), and excludes the military establishments and pipelines, as well as the transportation outside establishments.

In recent years, and in particular following the Fukushima accident in Japan, the EU significantly strengthened its legislative framework on nuclear safety by adopting the amended directive on nuclear safety in 2014 (European Union, 2014), the revised directives on basic safety standards in 2013 (European Union, 2013c) and the directive on radioactive waste and spent fuel management in 2011 (European Union, 2011). Altogether, this

BOX 1.2

INFORM – Index for Risk Management

INFORM is a global, open-source risk assessment for humanitarian crises and disasters. It can support decisions about prevention, preparedness and response. It is the first global, objective and transparent tool for understanding the risk of humanitarian crises. When all those involved in crisis prevention, preparedness and response use a shared risk assessment, they can work more effectively together. It has been developed in response to recommendations by numerous organisations to improve the common evidence basis for risk analysis as well as the real demands of Inform partner organisations. It is a way to simplify a lot of information about crisis risk so it can be easily used for decision-making. The Inform model is based on risk concepts published in scientific literature and envisages three dimensions of risk: hazards & exposure, vulnerability and lack of coping capacity dimensions (INFORM, n.d.).

represents the most advanced legally binding and enforceable regional legal framework in the world.

By the summer of 2017, EU Member States have agreed to implement the provisions of the amended nuclear safety directive in their national laws. An ambitious EU-wide safety objective for all types of nuclear installations has been introduced in this revised directive, with the aim of reducing the risk of accidents and avoiding large radioactive releases. This EU-wide safety objective will have a global impact via the 2015 Vienna Declaration on the International Atomic Energy Agency's Convention of Nuclear Safety.

In addition and in the post-Fukushima environment, the new Basic Safety Standards Directive modernises and consolidates the European radiation protection legislation and takes into account recent international recommendations and standards. Once fully implemented, the revised standards will bring the highest level of protection of workers, patients and the general public across Europe. It will also foster improvement in emergency preparedness and response regimes across Europe and will lead to better coordination and cooperation between Member States.

Specific policy instruments are also in place in the water sector related to extreme hydrometeorological events such as floods and droughts. Complementing the Water Framework Directive (WFD) (European Community, 2000), flood prevention and management are tackled by the European Union Flood Directive (European Community, 2007). In this framework, Member States should carry out a preliminary flood risk assessment on the basis of a methodology and accounting for historic floods, establish mechanisms to assess the flood hazard (e.g. extent and depth of water) and flood risk (i.e. the impact of significant flooding on health, the economy, the environment and cultural heritage) in Europe. This requires, for instance, knowledge of the location of floodplains and receptors within them, the use of advanced digital elevation models and the ability for elaborate modelling of the propagation of water during a flood — and the know-how to calculate damages arising from flooding. Based on the mapping, the design and implementation of a flood risk management plan with objectives and measures leading to the reduction of flood risk is carried out, which requires the use of prioritisation methods (e.g. based on cost/benefit) and an estimation of the likely impact of climate change in the longer term.

Water scarcity and droughts are also considered in the policy context. A European assessment of water scarcity and droughts has been conducted by the European Commission in this framework to monitor changes across Europe and to identify where further action is needed in response to climate change (European Commission, 2007). The successive steps of the WFD river basin management planning and the related flood and drought policy frameworks may conveniently incorporate adaptation to climate-related water risks through risk assessment, monitoring, environmental objective setting, economic analysis and action programmes to achieve well-defined environmental objectives. In addition, while the protection of the (coastal) marine environment is covered by the WFD, EU environmental policymakers considered there was a lack of strategy underpinning the policies to protect the marine environment. A strategy was thus developed in the sixth environmental action programme (2002-2012), which resulted in setting up environmental objectives for the marine environment. The related protection regime is regulated under the EU Marine Strategy Framework Directive, which was adopted in 2008 (European Community, 2008).

Finally, through its European Structural and Investment Funds, the EU provides important contribution to disaster prevention and management (European Union, 2013d); see Box 1.3. The regional dimension is central to disaster prevention, as local and regional authorities are the first to be confronted with the impacts of disasters. Disaster prevention is also important for regional development and cross-border action. Prior investment is safeguarded, as it is important in maintaining local growth and jobs. Investment in risk prevention itself can also develop new professional fields, foster innovation, support small and medium-sized enterprises (SMEs) and boost the transition to a low-carbon and climate-resilient economy.

1.3 Enhanced preparedness and response through timely, relevant and reliable information

The European disaster response coordination is ensured by the Emergency Response Coordination Centre (ERCC) to bring together scientific and operational communities in Europe in order to improve the planning of disaster response operations, including scenario building for disaster response, asset mapping and the development of plans for the deployment of response capacities. Timely, relevant and reliable information is vital for detection and alert systems at the core of disaster response activities. Forecasting and early warning tools supporting ERCC activities include the European Forest Fire Information System (EFFIS), the European Flood Awareness System(EFAS), the Medical Information System (MedISys), the Tsunami Assessment Modelling System and the European Drought Observatory (EDO).

The development and better integration of transnational and multi-hazard early warning systems by bringing together scientific centres around early warning systems is being strengthened through the EU project 'all risk integrated system towards' (Aristotle). The holistic early warning (INGV, 2016) is a unique project that has created a European scientific natural hazard partnership following a multi-hazard approach — consisting of 15 institutions, the majority of which are legally mandated to provide scientific advice in their national civil protection authorities as well — to support the ERCC. Aristotle is designed to be scalable in order to expand in the future to include other hazards and institutions, under the condition that the partnership and its structure prove to be solid and well functioning during this pilot phase. Aristotle was launched on 1 February 2016 and will last until 31 January 2018. Since 1 February 2017, it has become fully operational, providing the ERCC with 24/7 multi-hazard scientific analysis and advice for selected hazards (earthquakes, tsunamis, volcanic gases/ashes, floods and severe weather including tropical cyclones). This aims at increasing both preparedness and response levels of the ERCC and the UCPM participating states, all the while respecting the national responsibilities of the latter.

Disaster preparedness and response measures depend on the support of tools and instruments to provide timely, relevant and reliable data for operational decision-making.

BOX 1.3

EU Cohesion policy contributions to disaster risk prevention, 2014-2020

With EUR 8 billion for climate change adaptation and risk prevention and management, the cohesion policy is one of the most important sources for funding in this area. Twenty Member States have selected risk prevention as a priority for the 2014-2020 funding period, depending on their specific needs. Furthermore, risk prevention, disaster resilience and climate change adaptation are integrated into other cohesion policy-funding priorities, such as innovation, energy efficiency and water management. The planned investments increase Europe's resilience to disasters and climate change and aim at protecting 13.3 million people from floods and 11.8 million from forest fires (European Commission, 2016c).

Other tools are central to the operational activities of the European Commission, via the ERCC, such as the Copernicus programme (see section on Earth observation), and the Global Disaster Alert and Coordination System (GDACS), which provides key information on disasters worldwide and a platform for structured information exchange to facilitate decision-making in emergency responses (GDACS, n.d.).

Reinforcing access and use of sound data, evidence and DRM knowledge is also contributing to the development of an EU voluntary pool of pre-committed response assets to provide a basis for the identification of potential response capacity gaps and buffer capacities for use in extraordinary situations. Indeed, to increase the effectiveness and efficiency of the UCPM, the European Commission endeavours to foster technological innovation in response operations by encouraging the registration of innovative capacities in the ERCC.

The Copernicus programme provides accessible and global Earth observation through high-quality satellite mapping and services (European Union, 2014). Environmental information is of crucial importance to its activities and helps to understand how our planet and its climate are changing, the role played by human activities in these changes and how they will influence our daily lives. The Copernicus services address six thematic areas: land, marine, atmosphere, climate change, emergency management and security. The main users of the Copernicus services are policymakers and public authorities that need the information to develop environmental legislation and policies or to take critical decisions in the event of an emergency, such as a natural or human-induced disaster or a humanitarian crisis. In the area of DRM, Copernicus provides products such as maps identifying the extent of the disaster (e.g. delineation of the flooded area) and the level of damage (e.g. destroyed buildings in case of an earthquake).

Last but not least, better access to knowledge also benefits training networks, including the EU Trainet set up under the UCPM, which seek to create synergies through the exchange of experience, best practices, relevant research and other activities.

The EU Trainet is Lessons learnt activities also aim at providing a broader basis for knowledge development, also contributes to enhance the knowledge base in DRM (European Union, 2013a).

1.4 A robust knowledge base for disaster risk management

The Union's multiannual research and innovation framework programmes support a range of research and innovation projects relevant to disaster management (European Union, 2013e); see Box 1.4. Multinational and interdisciplinary research in the field of natural and technological disasters has led to the development of innovative tools and methodologies to forecast and monitor man-made and physical hazards.

On the other hand, research efforts in support of risk management and crisis management have largely contributed in the preparedness and response to major crises and have therefore helped reduce the toll on human lives and economic assets.

A risk-informed approach to DRM is built upon a robust and extensive knowledge base: research, innovation and scientific projects are central components

The European Commission's Community of Users on Secure, Safe and Resilient Societies aims to make better sense of available research and identify research needs through stronger networks and exchange of information.

The Community of Users built around EU research and the Disaster Risk Management Knowledge Centre will be mutually reinforcing the EU's efforts to strengthen the interface between policy and science and pave the way for a risk-informed approach to EU policies.

The importance of knowledge for climate change adaptation planning is recognised in the EU Adaptation Strategy: one of the pillars of the Strategy rests on refining the knowledge gap for adaptation to promote better-informed decision-making (European Commission, 2013b). The development of the one-stop-shop for adaptation, Climate-ADAPT, contributes to improving accessibility and usability of information on and relevant to climate change adaptation. This public platform contributes to strengthening the knowledge base and providing valuable data and sources to inform policymakers and other stakeholders (Climate-ADAPT, n.d.).

European efforts towards enhanced urban resilience to disasters also risks requires strengthening the contribution of science and innovation to enhance the resilience of urban settings as well as integrating urban risk management into national DRR strategies and sustainable development planning. The Global Human Settlement Layer (GHSL) framework, developed by the European Commission will produce new global spatial information, evidence-based analytics and knowledge describing urban settlements on the planet. This information will be instrumental in assessing the impacts of DRM policies on development trends and patterns in a consistent and detailed manner.

In the field of humanitarian relief, the European Commission contributes to building the capacity and to shaping the governance of the international humanitarian system through the Enhanced Response Capacity funds, which aim to support coordination structures for the delivery of humanitarian assistance like the global humanitarian clusters and stand-by expertise for emergencies, as well as studies and guidelines on specific aspects of humanitarian assistance and platforms and networks for learning and knowledge sharing (European Commission, 2015). The European Commission also ensures, through scientific tools such as the EU Aid Explorer, to make aid data easily accessible to ensure aid effectiveness and accountability and to reinforce the evidence base for policymaking. Maps and graphs are developed to support operations as well as to

BOX 1.4

Examples of relevant Horizon 2020 research priorities

Under the current EU framework programme for research and innovation Horizon 2020, the societal challenge chapters on 'Secure societies' and 'Climate action, environment, resource efficiency and raw materials' address the research needs across prevention, preparedness and response actions in the areas of crisis management, disaster resilience, climate change, critical infrastructure protection and sustainability. In light of this new direction, vulnerability studies, integrated risk assessments and DRM strategies are increasingly considering the social, economic, environmental and health dimension of the risk.

Developing the awareness and demonstration of the added value of risk mitigation and adaptation approaches in terms of co-benefits for local economies, social cohesion and the broader environment will be further supported by demonstration projects and other EU funds programmes.

Research needs for humanitarian aid are also addressed by Horizon 2020, such as with calls focused on advancing theoretical and practical knowledge on EU response mechanisms and their effectiveness (INT-5-2015) or the development of civilian humanitarian mission personnel tracking (BES-10-2015).

Climate services, nature-based solutions for building more resilient cities or territories, and dynamic earth observations are examples of promising sectors. Heightened emphasis in DRR and resilience building in urban areas is also becoming increasingly central to sustainable urban development (European Union, 2016). The Horizon 2020 research programme has a strong focus on social, technological, digital and nature-based innovation in urban planning and policy formulation.

visualise the distribution of aid across countries and sectors worldwide (EU Aid Explorer, n.d.).

The EU was one of the first development donors to develop a dedicated resilience policy aiming to strengthen the resilience of communities and their livelihoods and ecosystems as a core objective for humanitarian and development aid (European Commission, 2012, 2013a). A new European consensus on development has been made to guide all of the EU and its Member States' development policy activities (European Commission, 2016d) and under which they should increase efforts to build resilience and adaptability to change.

In this context, the EU is committed to reinforcing the science and policy dimension of DRR both within the EU and in support to crisis-prone developing countries in line with priority areas of the Action Plan for Resilience in Crisis Prone countries. The EU supports developing countries, in particular Least Developed Countries (LDC) and Small Island Developing States (SIDS), to develop DRR policies capacities and mainstream DRR, climate change adaptation and the protection of ecosystems or protected zones (see Box 1.5).

1.5 Coherent international processes and the role of science

The European Commission is fully committed to being a frontrunner in the implementation of the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). Science and innovation contribute to several SDGs and their associated targets; for instance, they feature prominently within SDG 17 on means of implementation and

BOX 1.5

Examples of programmes and projects to support implementation of DRR and climate change policies in EU development cooperation

The global thematic project, 'Building capacities for increased public investment in integrated climate change adaptation and disaster risk reduction: 2012-2015', covers 40 vulnerable developing countries that were supported between 2013 and 2016 in a partnership with the United Nations Office for Disaster Risk Reduction (UNISDR) to build and improve national disaster loss databases for disaster loss accounting. Among these 40 countries, 30 have progressed further in capacity building to develop and use probabilistic risk assessments and 20 have been supported in integrating risk-informed planning in different sectors of development, with a focus on public investments. This partnership project further supported the preparation of the Global Assessment Reports (UNISDR, 2015) by providing the means to conduct modelling and investigate disaster risk from the national to the global level.

In addition, the EU supported the elaboration and publication of the African, Caribbean and Pacific (ACP) Compendium of Risk Knowledge (Morinière and Zimmerman, 2015) through the 10th European Development Fund intra-ACP programme as part of its support for DRR in partnership, among others, with the ACP group of countries and regional organisations.

Since 2007, with the launch of the Global Climate Change Alliance (GCCA), more than 50 projects in 35 countries have been implemented under its flagship programme contributing to the resilience of the communities and their livelihoods and vulnerable ecosystems.

the global partnership, SDG 9 on resilient infrastructure and inclusive, sustainable industrialisation and SDG 11 on making cities inclusive, safe, resilient and sustainable. The European Commission will support the implementation of the 2030 Agenda for Sustainable Development, firstly by mainstreaming the SDGs in the European policy framework and current European Commission priorities and secondly by launching a reflection on further developing our longer-term vision and the focus of sectoral policies after 2020 (European Commission, 2016d, 2016e).

The Addis Ababa Action Agenda (an integral part of the 2030 Agenda for Sustainable Development) sets out a comprehensive range of policies and actions, including science, technology and innovation, which are needed to achieve the ambitious vision set out in the SDGs (UNGA, 2015a).

The World Humanitarian Summit, organised in 2016 as a response to an unprecedented increase of people affected by conflict and natural disasters, put forward a number of key commitments to place the safety of people, dignity and the safeguard of human rights at the heart of decision-making (WHS, 2016). In its support to the commitments made, the EU will rely on the support of a number of scientific tools and platforms, some of which were developed by the European Commission and its key partners; see Box 1. 6.

The United Nations Sendai Framework for DRR shifts the emphasis from response-oriented disaster management to comprehensive DRM, in which a more systematic and reinforced science-policy interface strengthens the contribution of DRM to smart, sustainable and inclusive growth globally (European Commission, 2016a). The framework calls for a strong interface between science and policy to build a strong knowledge of disaster risk; make efficient use of data to better understand the economic impacts of disasters; and develop adequate preventive policies to reduce the risks of disasters (UNGA, 2015b); see Box 1.6.

At a global level, science and technology play a central role in the 2030 Agenda for Sustainable Development and other international agreements addressing DRM

In the context of the Paris Agreement on climate change (UNFCCC, 2015), the importance of data collec-

BOX 1.6

UNISDR Science and Technology Conference on the Implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2016)

The outcomes of the 2016 UNISDR Science and Technology Conference underline that the science and technology community should support the implementation of the Sendai framework through:
- original research and investigation;
- the assessment and analysis of hazards and the consequences of cascade effects;
- the development and validation of applied tools and standards;
- the design and use of new technologies;
- a range of education and communication roles.

More generally, ensuring the integration and promotion of a holistic approach to the science of hazards will be an important contribution to reinforcing the science-policy interface around DRM.

tion, evidence-based approaches and the contribution of science was recognised. Science is needed to inform and provide tools to achieve the target specified in the climate deal, both for adaptation and mitigation, and to contribute to taking stock of progress. The Intergovernmental Panel on Climate Change (IPCC) was invited to produce a special report by 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways.

As illustrated by the New Urban Agenda agreed at the Habitat III Conference on Housing and Sustainable Urban Development, the international community has come to acknowledge how essential greater attention to urban needs is when addressing DRM, climate adaptation and urban resilience. Unique and emerging development challenges facing all countries are given particular attention for the implementation of the New Urban Agenda. Commitments such as the support for disaster risk assessments; the development of standards for levels of risks and of quality infrastructure and spatial planning; and most of all the mainstreaming of data-informed DRR and DRM at all levels reinforce the relevance of an integrated science-policy interface to ensure environmentally sustainable and resilient urban development (UNGA, 2016).

1.6 Towards a stronger science-policy interface

Faced with the risk of increasingly severe and frequent natural and human-induced disasters, policymakers and risk managers in DRM and across EU policies increasingly rely on the wealth of existing knowledge and evidence at all levels — local, national, European and global — and at all stages of the DRM cycle — prevention and mitigation, preparedness, response and recovery.

Many policies at EU level as well as political initiatives on a global scale include a disaster risk dimension. Ensuring a robust DRM knowledge base is essential to informing these different policy processes and to working towards effective evidence-based decision-making.

Reinforcing the science-policy interface should allow for better exploiting and translating the complexities of scientific results into useful and usable policy outputs through efficient access and uptake of knowledge and research, a networked approach across relevant stakeholder communities and continuous efforts towards innovation and new technologies and tools.

The Disaster Risk Management Knowledge Centre (DRMKC, 2017) launched by the Commission on 30th September 2015 offers a valuable platform to meet these aims and further enhance the contribution of science to DRM policymaking. The Knowledge Centre implements a networked approach to translate complex scientific data and analyses into usable information at all stages of the disaster risk management (DRM) – from prevention to recovery – and at all levels – local, national, European and global - to provide science-based advice for DRM policies, as well as timely and reliable scientific-based analyses for emergency preparedness and response coordinated activities.

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Disaster
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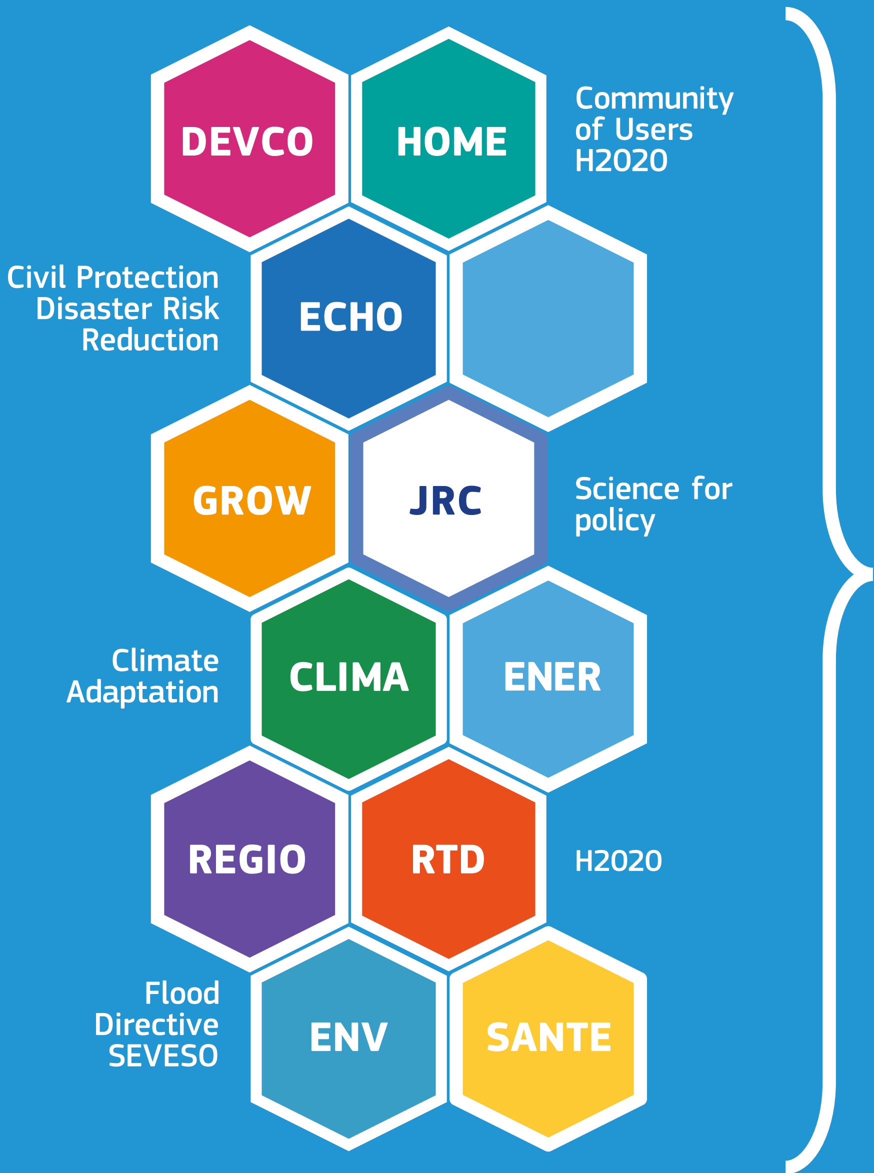
DRMKC

Large scientific community for **DRM**

EC Directorates



DRMKC

PARTNERSHIP

1 Hazard Scientific Partnerships

2 Science Policy Interface

KNOWLEDGE

3 Pooling of Research Results

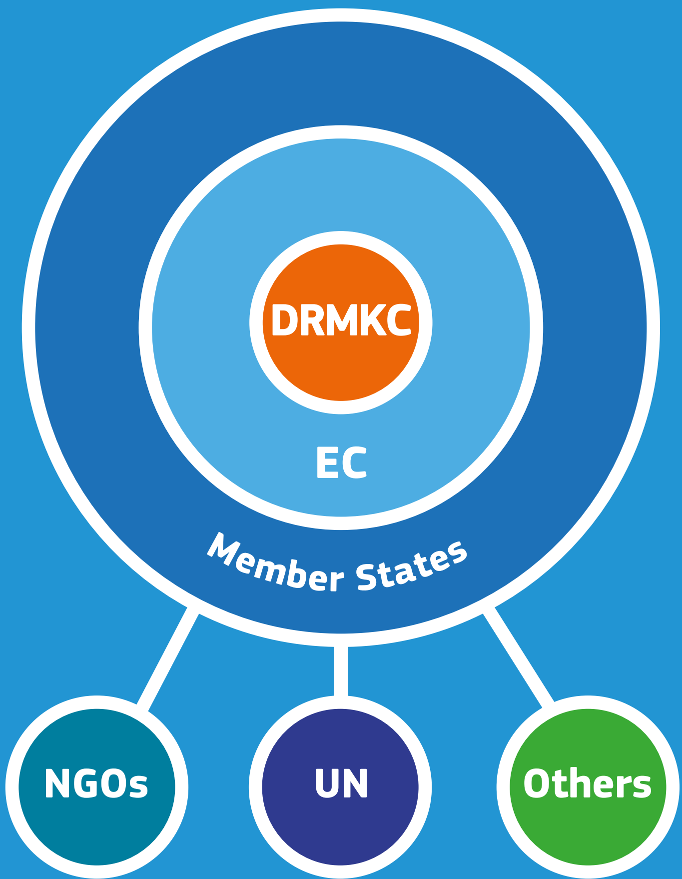
4 Identification of research needs and gaps

INNOVATION

5 Networks of Laboratories

6 Support System

Serving



Chapter 2

Understanding disaster risk: risk assessment methodologies and examples

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2 Understanding disaster risk: risk assessment methodologies and examples

CONTENTS

Introduction

Definition of risk

There is no commonly accepted definition of risk. According to the United Kingdom's Royal Society (1992), risk is 'the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge'. By contrast, the latest UNISDR's definition (2017) of disaster risk is 'the potential loss of life, injury, destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity'.

Disaster risk is not just about the likelihood and severity of the hazard event but also about what is exposed to that hazard and how vulnerable that exposure is. A severe earthquake in a relatively uninhabited region can be of far less consequence than a relatively minor one near a large conurbation. Similarly, a severe earthquake in an area known to be prone to earthquakes and so with strict design and construction standards can cause fewer fatalities and less damage than an unexpected, much smaller one in an unprepared area with poor building standards.

Following the Sendai disaster risk definition, we may consider risk to comprise of three elements.

1. Hazard: the adverse event causing the loss.
2. Exposure: the property, people, plant or environment that are threatened by the event.
3. Vulnerability: how the exposure at risk is vulnerable to an adverse event of that kind.

Note that the forth Sendai element; capacity, the ability of the system to respond after the event to mitigate the loss, is generally considered to be a component of vulnerability. Loss suffered, that is the damage caused to the exposure at risk to a defined hazardous event, will depend upon these elements.

Risk complexity and dependency

Single events may have no one single cause. For example a major flood could be caused by a combination of one or more of heavy rain, unseasonably high temperatures causing snow to melt fast, baked land from a prior dry spell or conversely saturated soil from earlier continuous rains, which both increase run-off, high tides and storm surge.

Whilst it is sometimes difficult to consider risks from a single hazard, what of their combinations? The major cause of death and damage following the Great Kantō earthquake affecting Tokyo in 1923, an event that left more than

140 000 people dead or missing, was not from building collapse due to ground shaking but from fire storms provoked by cooking equipment knocked over in the event. Similarly, earthquakes may cause tsunamis, landslides, dam failures or avalanches and windstorms may cause landslides, storm surge, floods or flash floods. Vetere Arellano et al. (2004) includes a fascinating example of cascading risk following an earthquake in Turkey in 1999.

Human action can also affect the loss. For example, canalising rivers or building on historical floodplains can give excess flood water nowhere to go; wide-scale concreting over gardens to provide hard standing for motor cars prevents water absorption, perhaps exacerbated by inadequate or poorly maintained drains. What historically would have been a benign event can now become a calamitous one.

Uncertainty and subjectivity

Risk includes elements of the scientific and the subjective. In some hazards or sectors, risk can be clearly defined. For example in the insurance industry, the 'risk business' defines property or people who are normally insured against defined hazards with payment made upon financial loss suffered. As we will discuss later, this has led to an explosion in risk analytics over the last 30 years, leading to a far more technically sophisticated but also financially secure insurance industry.

However, even here there are limits in what we know. We may feel we know how well a particular building will react to an earthquake of a certain intensity, but do we know it was built to the right standard or correctly maintained? We may feel we can reasonably estimate the damage that a flood with a depth of 1 metre can do to an industrial plant, but how well can we estimate the firm's economic loss related to this damage, which will depend on how quickly the plant may be repaired or replaced, on whether it has any other factories available to take some of the strain and on whether business temporarily lost can ever be fully regained.

There is an inherent uncertainty, as by definition catastrophes are rare events; data to describe their effects may be partial, at best. However, as we will discuss later on, the process to understand and model risk sheds light on areas where data are lacking and therefore where additional focus is required. Subjective assumptions, perhaps currently unstated, must be made explicit and so held up for discussion.

Risk is not static but rather dynamic and dependent upon changes to hazard, exposure and vulnerability. Anthropogenic climate change is accepted as scientific fact, but its consequences on a local level and for a particular hazard may not be clear. Historical observations are often limited, partial and contaminated with natural variation and underlying factors that may not be fully understood. But clearly there is a public and therefore political pressure for governments to protect their populations against the impacts of climate change. In practice, though, the risk as it is now is very often not properly understood, and still less how it may worsen (or conversely improve) under different climate change assumptions in 30 years' time; understanding current risk is fundamental to understanding how that risk may change in the future.

Risk perception

When we begin to move into exposure, such as the preservation of habitat and/or animal population, it may be harder to place an agreed value on preservation or qualification of damage if either is impaired, even where there is common acceptance of the importance of the risk to society. A common risk metric must be agreed in order to allow, for example, the relative social and environmental cost of sacrificing an important ecological habitat to protect the human population of a city.

Humans have short memories; current risk concerns may be driven by recent experience rather than underlying loss potential. Few were concerned with tsunami risk until the tragic events of 2004 and 2011 — the risks were theoretically known but were rare, and crucially as no significant tsunami had been filmed until 2004, the risk was difficult to relate to and was often overlooked.

Indeed, perception of risk drives policy (Klinke and Renn 2002). For example, many more die on the road than in train crashes, but these deaths tend to come in ones and twos at any time, rather than several casualties, as in rail crashes. Post-loss this may lead to calls to improve the already relatively safe rail system when a similar amount spent on the road network may save more lives.

The public purse is not unlimited. Should the politician react to the public perception of risk by spending on risk prevention in areas of known public concern or try to assess the range of risks the population face and prioritise spending on a more rational cost/benefit approach? In the short term, pre-event, the former will be more electorally advantageous but the post-event failure to react to an unrecognised hazardous eventcould have enormous political as well as human consequences. It is vital to consider not just what has happened but what could happen; taking action to minimise loss in advance and not just reacting to events as they occur.

Recognising risk may also have its consequences. Many societies have a pressure on housing. Flood plains offer an easy solution, the land drained, defences constructed and houses built, which is popular as people like living near water. But how robust are the new properties in a changing climate? Can risk be overlooked if there is a social need? Certainly before the event, but what about after? What if the properties become uninsurable and so unsaleable?

The importance of understanding disaster risk

Risk is complicated, but understanding risk is vital to the proper protection of society and the environment. Without proper risk analysis, can appropriate policy decisions be made?

In an increasingly litigious society, could governments and officials not have a proper risk assessment methodology? It is vital to understand and use the best science, but ultimately policymakers will also necessarily react to stakeholder perception. It is hoped that scientific fact, properly presented, will drive perception, but ultimately risk management decisions are necessarily political.

Those decisions need to be made in a transparent manner; open to scrutiny, challenge and debate. It is impossible to completely eliminate risk, even with an unlimited public purse. In reality, budgets are under pressure, with many calls upon limited funds: spending money on preparing for an event that will probably not even occur within a politician's period of office may not be as high a priority as trying to address an immediate social need.

However, there is a duty of care to protect the citizens and the natural environment of Europe. Modern risk assessment, coupled with risk and financial modelling, provides the framework to make the right decisions for both now and the future.

2.1 Qualitative and quantitative approaches to risk assessment

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2.1.1 Risk assessment

2.1.1.1 The importance of risk assessment

Risk assessment is a means not only to understand the risks that society (or a family or business) faces, with their potential probabilities and impacts, but also to provide a framework to determine the effectiveness of disaster risk management, risk prevention and/or risk mitigation.

It would be spurious to pretend that we fully understand all the hazards that society faces and their potential consequences. The process of risk assessment requires a structured approach. Without such a process, risks may be overlooked or implicit assumptions may be made. A risk assessment process requires transparency, opening up assumptions and options to challenge, discussion and review.

A structured approach is required to understand all the hazards that society faces and their potential consequences. This requires transparency, opening up assumptions to challenge, discussion and review.

Risk assessment and mapping guidelines for disaster management (European Commission, 2010) and Overview of natural and man-made disaster risks in the EU (European Commission, 2014), provide a solid outline of the issues in a European context. The first outlines 'the processes and methods of national risk assessments and mapping in the prevention, preparedness and planning stages, as carried out within the broader framework of disaster risk management', whereas the second paper analyses 18 national contributions, identifying 25 hazards, both natural and man-made (malicious and non-malicious).

However, as an example of the importance of risk assessment, the experience of the insurance industry is presented, an industry that has been transformed by the adoption of an increasingly rigorous risk assessment and modelling process over the last 30 years. The lessons learnt are relevant to policymakers and practitioners in government.

2.1.1.2 Example: catastrophe risk and the insurance industry

As recently as the 1980s, the insurance industry's catastrophe risk assessment was almost entirely based on historical experience or 'rule of thumb' assumptions. Catastrophes are, by definition, rare events. It is very unlikely that a mega event will have occurred in recent years and, even if that were the case, it may have had unique features that may not reoccur. If we had a historical event, would it cause similar damage if it reoccurred? The global population is growing and getting wealthier, with the majority now concentrated in cities. Pressure of population growth has created the need to build on land that was wisely avoided by our forefathers. Growth may be unplanned with infrastructure, such as drainage not keeping up with the rate of development. People like living close to water, potential loss may be more than just scaling the historical loss by population change and wealth.

The need for a better approach was clear. In 1984 Don Friedman published a paper that would form the template for modelling insurance catastrophe risk over the following 30 years, breaking the process into hazard, exposure, vulnerability and financial loss. The first United States hurricane model to this template was produced by the reinsurance broker E.W. Blanch in 1987 (White and Budde, 2001), followed by the United States earthquake in 1988. Reinsurance brokers and reinsurers also lead the field in Europe; however, the early 1990s saw the rise of three major catastrophe modelling firms, which still dominated the industry in 2016.

These models were stochastic models — based not on a few historic hazard events but rather on a synthetic event made of many thousands of events that attempt to represent the range of possible events with their associated probabilities. The models required knowledge not only of what properties were insured and their value but also of their location, construction type and occupation. Engineering principles augmented by historical loss analysis attempted to understand the relationship between the event's manifestation at a particular location (e.g., peak ground acceleration, peak gust speed and maximum flood depth) and its likely damage. From this an overall damage estimate for any given property portfolio for each of the synthetic events could be calculated. If the probability of each synthetic event is then applied, we could understand the distribution off loss to the overall portfolio, for example what the annual average loss is and how big a loss from that hazard type can be expected every 5, 10, 20, 50 and 100 years.

The process of modelling catastrophe risk has transformed the reinsurance industry by increasing knowledge, scientific engagement, technical competence and, most importantly, the resilience of the industry — its ability to pay claims.

Decisions could be made based on 'objective fact', not subjective opinion. Underwriters now had much more information to appropriately rate individual policies and to decide how much total risk they could accept across their portfolio and how much to off lay. The concept of risk/return entered the market. Firms began to clearly define their risk appetite to ensure appropriate levels of financial security and then seek to maximise return within that appetite.

It has not been a painless process. Initially, many saw the models as a panacea to the market's problems. There was a tendency by those unaware of the complexity of the models to believe the results. Arguably, the models were oversold and overbought: the vendors sold the models on their technical capabilities and the buyers bought them seeking certainty, but neither publically faced up to the inherent uncertainty within the models, despite growing pains in the process. However, this information has transformed the industry. Twenty years ago the most technical reinsurance broker had perhaps 3 % of staff engaged in risk analytics, whereas now this has become 25 % to 30 %. Chief risk officers were virtually unknown in the insurance industry 20 years ago; now they are embedded.

The models became a mechanism to raise debate above vague opinion to a discussion of the veracity of assumptions within the model. The models' data requirements led to a massive increase in the quality and quantity of data captured, leading in turn to improved models. Knowledge of catastrophe risk has grown immeasurably; firms have become smarter, more financially robust and therefore more likely to meet their claim obligations.

Whilst such modelling originally applied to catastrophe risk only, it has been extended to cover man-made hazards such as terrorism and more esoteric risk such as pandemic. Indeed, the EU's solvency II (Directive

2009/138/EC) an insurance regulatory regime, requires firms to understand all the risk they face, insurance and non-insurance (e.g., market risk, counterparty risk and operational risk), with the carrot that if they can demonstrate that they can adequately model their risks, then they may be allowed to use the capital requirement implied by their model rather than the standard formula. Regulators rather smartly realise that any firm willing and able to demonstrate such capacity and understanding is less likely to fail.

2.1.1.3 The key elements of risk assessment

Whilst the insurance industry is a special case, others are noticing that the same methods can be used to manage risks to governments, cities and communities. They can drive not only a better understanding of the risks that society faces but also a means to determine and justify appropriate risk planning, risk management strategies as well as public and investment decisions.

Risk assessment requires the identification of potential hazards as well as a knowledge of those hazard including their probability, what is exposed to that hazard and the vulnerability of that exposure to the hazard.

Indeed, it can be argued that the process of risk assessment and modelling is more important than the results obtained. Risk assessment does not need to be as complex as a full stochastic model to add real value. Similarly, it is a common misunderstanding that a lack of good-quality, homogeneous data invalidates risk assessment. Any risk assessment methodology requires assumptions to be brought to light and so opened to challenge. Assumptions can then be reviewed, compared and stressed, identifying areas of inconsistency, illogicality, sensitivity and where further research should be concentrated.

The key steps in risk assessment are the following.

- Identify the hazards which might affect the system or environment being studied A brain-storming session to identify all potential hazards should be done at an initial stage. It is important to think beyond events or combinations of events that have occurred in order to consider those that may occur.

- Assess the likelihood or probability that hazards might occur: inputs to this process include history, modelling, experience, corporate memory, science, experimentation and testing. In practice, events with a very, very low probability (e.g. meteor strike) are ignored, focussing on ones more likely to occur and can be either prevented, managed or mitigated.

- Determine the exposure to the hazard, i.e. who or what is at risk.

- Estimate the vulnerability of that hazard to the entity exposed in order to calculate the physical or financial impact upon that entity should the event occur. This may be obtained by a review of historical events, engineering approaches and/or expert opinion and may include the ability of the system to respond after the event so as to mitigate the loss.

- Estimate the potential financial and/or social consequences of events of different magnitudes.

2.1.1.4 Risk tolerance

The likelihood of the hazard and its consequences needs to be compared with the norms of tolerability/acceptability criteria that society or an organisation has formulated. If these criteria are met, the next step would be to manage the risk so that it is at least kept within these criteria and ideally lowered with continuous improvement.

If the risk criteria are not met, the next step would be risk reduction by either reducing exposure to the hazard or by reducing vulnerability by preventative measures or financial hedging, typically through traditional indemnity insurance that pays upon proof of loss, but also increasingly through parametric insurance that pays upon proof of a defined event occurring. Insurance-like products can also be obtained from the financial markets by means of catastrophe or resilience bonds.

In industry, reducing event likelihood is normally the preferred method, since this dimension is amenable to improving reliability and enhancing the protective measures available. In many cases, these can be tested, so are therefore often a dominant feature of risk reduction. Estimating the potential severity of the hazard is harder and often leaves much to expert opinion. If risk cannot be credibly reduced in industry, it may lead to the cessation of an activity. Ideally, a hazard would be completely avoided: a fundamental step in the design of inherently safer processes.

However, for natural hazards and climate risk, where hazard likelihood reduction is often impossible, it is required to work on exposure and vulnerability. Building codes, for example the EU standard Eurocodes, encourage appropriate resilience in design and construction and can include 'build back better' after an event. Spatial planning and the delineation of hazard zones of various levels can promote development in areas less exposed to risk.

Risks can never be eliminated but they can be managed and their consequences reduced, at a cost. Defining risk tolerance allows informed, cost-effective risk management decisions.

The insurance mechanism can be used to encourage appropriate risk behaviours, penalising poor construction, maintenance or location by reduced cover or higher premiums and rewarding mitigation measures, e.g. retro-fitting roof ties in tropical cyclone-exposed areas or installing irrigation systems for crops by premium reductions.

2.1.2 Risk identification process

2.1.2.1 The importance of risk identification

It is necessary to identify unwanted hazardous events (i.e., atypical scenarios) and their consequences. It is very important to include all these in a study. If a possible hazard is overlooked, it will never be assessed. Unfortunately, there are many examples of this failure (Gowland, 2012).

In all risk assessment methods, the failure to include these 'atypical' scenarios will present problems. Examples include the major fire and explosion at Buncefield (December 2005) and the tsunami that inundated the Fukushima nuclear power station (March 2011). Identification of all potential hazards is absolutely fundamental in ensuring success.

The United Kingdom Health and Safety Executive has identified and reviewed almost 40 hazard identification methods.

The scope and depth of study is important and relevant to purpose and the needs of users of the assessment. It is necessary to identify all hazards so that a proper risk assessment may be made. When we are open to considering potential deviations we need to make sure that we are open-minded enough to consider all possibilities even when they may seem to be remote.

It is important to consider all potential hazards, natural and man-made, and their possible interactions and consequences. The process should not be limited to events known to have happened in the past, but also to consider what could happen.

Methods in use greatly depend on the experience of the persons carrying out the study. This is normally a team activity, and how it is made up is important and should be drawn from persons familiar with the technology or natural phenomena and the location being considered. Techniques adopted range from relatively unstructured 'brainstorming' through to the more structured 'what if' analysis.

Potential risks may not be obvious and may not have occurred in the past. It is vital to seek to identify what could occur as well as the consequences.

Other more formalised processes exist in industry, though, including failure mode and effect analysis (FMEA) and the highly structured hazard and operability (HAZOP) study, both of which look to identify hazardous events and to locate causes, consequences and the existing preventive measures. FMEA was developed for the automobile industry and HAZOP was developed for the chemical and process industry. However, similar studies can be applied to any field of risk. For example, the HAZOP (Tyler et al., 2015) use of guide words and deviations, which might seem to be limited to the industry where first applied, can be adjusted or replaced with those relevant to the field being studied; this has been demonstrated in the mining industry in Australia, where modified chemical industry methods have proved useful.

2.1.2.2 What if

This is a form of structured team brainstorming. Once the team understands the process or system being assessed and the kind of risks (potential exposures and vulnerabilities), each discreet part or step is examined to identify things that can go wrong and to estimate their possible consequences.

A team of experts brainstorming is one way to flush out potential risks, but it is important to use a panel of experts whose experience covers all aspects of risk.

In order to carry this out successfully, we must stress the need for the team to be properly qualified and to have a full set of data relating to the system being studied. This would include operating instructions, process flow sheets, physical and hazardous properties of the materials involved, potentially exposed persons, environment or assets, protective systems. Most users will simply estimate the likelihood and severity of consequences in a similar way to that used in risk matrix applications.

A brainstorming exercise has the side benefit of encouraging a wide participation in the risk identification and assessment process, increasing ownership of the ultimate conclusions.

2.1.2.3 Failure mode and effect analysis (FMEA)

FMEA is a rigorous, step-by-step process to discover everything that could go wrong in a task or process, the potential consequences of those failures and what can be done to prevent them from happening. In this way, it can be used in risk assessment in industry. As shown in Figure 2.1, it comprises a systemised group of activities designed to:

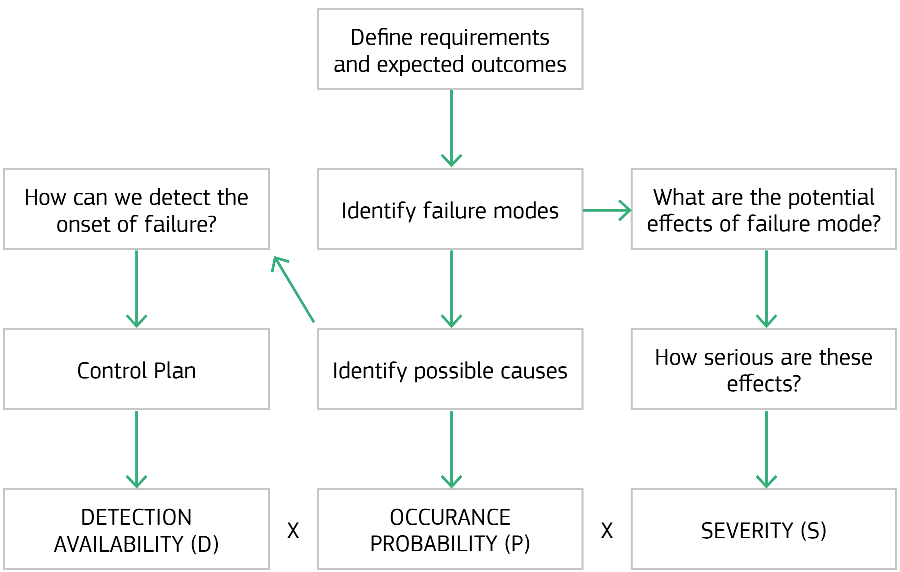
- recognise and evaluate the potential failure of a process or equipment and their effects;
- identify actions which could eliminate or reduce the chance of potential failure;
- document the process.

It captures:

- the failure mode, i.e., what could go wrong;
- the effect analysis, i.e., how it would happen, how likely it is to go wrong and how bad it would be.

FIGURE 2.1

A graphic illustration of the FMEA process. Source: courtesy of authors



A very good example of a high-risk and high-priority project is the space shuttle where we put fragile human lives in a tin can and send them to space, hoping to get them home safely. Considering the complexity of the shuttle, there are many possible items which can fail, and they all have individual failure modes and effects. Lives are at risk and space shuttles are expensive. FMEA is a tool used to provide a structured process to understand and thereby minimise risk.

FMEA is a structured what-if process widely used in the process industries and provides a template for other potential applications.

The three distinct assessments for each of the three strands of this methodology, detection availability, occurrence probability and severity, are each given a rating: D, P and D, respectively. Risk ranking is calculated by multiplying these factors to give a single rating D x P x S. A risk matrix may be used to illustrate this process (see Chapter 2.1.4.3.).

2.1.2.4 Hazard and operability study (HAZOP)

The technique of HAZOP has been used and developed since the 1970s for identifying potential hazards and operability problems caused by 'deviations' from the design intent of a part of a production process or a procedure for new and existing operations. The technique is most associated with identifying hazardous deviations from the desired state, but it also greatly assists the operability of a process. In this mode it is very helpful when writing operating procedures and job safety analysis (Tyler et al., 2015).

Processes and procedures all have a design intent which is the desired normal state where operations proceed in a good way to make products in a safe way.

With this in mind, equipment is designed and constructed, which, when it is all assembled and working together, will achieve the desired state. In order to achieve this, each item of equipment will need to consistently function as designed. This is known as the 'design intent' for that particular item or section of the process.

HAZOP is a what-if process identifying potential hazards caused by 'deviations' from the design intent of a part of a production process or procedures.

Each part of this design intent specifies a 'parameter' of interest. For example, for a pump this could be flow, temperature or pressure. With a list of 'parameters' of interest, we can then apply 'guide words' to show deviations from the design intent. Interesting deviations from the design intent in the case of our cooling facility could include less or no flow of water, high temperature or low (or high) pressure. When these deviations are agreed, all the causes associated with them are listed. For example, for no or less flow, causes will include pump failure, power failure, line blockage, etc.

The possible hazardous consequences can now be addressed, usually in a qualitative manner without significant calculation or modelling. In the example, these might be, for example, for line blockage pump overheats or loss of cooling to process, leading to high temperature problems with product.

These simple principles of the method are part of the study normally carried out by a team that includes designers, production engineers, technology specialists and, very importantly, operators. The study is recorded in a chart as in the study record. A decision can then be made about any available safeguards or extra ones that might be needed — based on the severity or importance of the consequence.

It is believed that the HAZOP methodology is perhaps the most widely used aid to loss prevention in industry. The reason for this can be summarised as follows:
- it is easy to learn;
- it can be easily adapted to almost all the operations that are carried out within process industries;
- no special level of academic qualification is required.

2.1.3 Risk analysis methodologies

2.1.3.1 Types of risk analysis

Risk analysis is a complex field requiring specialist knowledge and expertise but also common sense. It is not just a pure scientific field but will necessarily include judgements over issues such as risk appetite and risk management strategy. It is vital that the process be as comprehensive, consistent, transparent and accessible as possible. If a risk cannot be properly understood or explained, then it is difficult if not impossible for policymakers, companies and individuals to make rational choices.

The appropriate form of risk analysis will depend on the purpose and the data available from simple scenarios to full probabilistic analysis, but all can lead to better decision-making.

Currently, there is no universally agreed risk analysis method applied to all phenomena and uses, but the methods used rather are determined by a variety of users, such as industrial and transport companies, regulators and insurers. They are selected on the basis of their perceived relevance, utility and available resources. For example, a method adopted in industry may not be suitable in the field of natural hazards. Legal requirements may also dictate the degree of study as well as such factors as the 'allowable' threat to the community. This last matter is common in 'deterministic' risk analysis where the requirement may be that there is no credible risk for a community in the location of an industrial operation.

Deterministic methods consider the consequences of defined events or combinations of events but do not necessarily consider the probability of these events or guarantee that all possible events are captured within the deterministic event set. Often this is the starting point for risk analysis. At the other extreme, stochastic or probabilistic analysis attempts to capture all possible outcomes with their probabilities; clearly coming with a much higher data and analytical requirement and, if correct, forming the basis for a sophisticated risk assessment process.

2.1.3.2 Deterministic methods

Deterministic methods seek to consider the impact of defined risk events and thereby prove that consequences are either manageable or capable of being managed. They may be appropriate where a full stochastic model is impossible due to a lack of data; providing real value whilst a more robust framework is constructed.

Risk standards may be set at national and international level and, if fully complied with, are believed to prevent a hazard that could impact the community. This is akin to the managing of risk in the aviation industry, where adherence to strict rules on the design and operation of aircraft and flights has produced a very safe industry. The same approach to rule- based operations exists in some countries and companies.

How are deterministic events framed? For example, to check the safety of an installation against a severe flood, severity is assessed according to the worst recently seen, the worst seen in the last 20 years or the worst that may be expected every 100 years based on current climatic conditions and current upstream land use. A different choice of event will have a different outcome and potentially a very different conclusion about manageability. Can we ensure that all deterministic events used in risk assessment across hazards are broadly equivalent in probability? If not, assessments and conclusions may be skewed.

Deterministic methods seek to consider the impact of defined risk events and thereby prove that consequences are either manageable or capable of being managed.

In recent times there has been a shift from a totally rule- based system to one where an element of qualitative, semi- quantitative and quantitative risk assessment (QRA) may influence decisions. But deterministic risk assessment is also carried out as a reality check for more complex stochastic models and to test factors that may not be adequately modelled within these models.

For example, over the past 20 years the insurance industry has enthusiastically embraced advances risk assessment techniques, but deterministic assessment of the form 'if this happens, this is the consequence' is still required by regulators. They may be referred to as:

- a scenario test, where a defined event or series of events is postulated and the consequences assessed;
- a stress test, where pre-agreed assumptions of risk, for example implied within a business plan (e.g. interest rate assumptions), are stressed and challenged to determine their impact on results and company sustainability;
- a reverse stress test, where events or combinations of events are postulated that could cause insolvency of the firm if unhedged.

Scenario, stress and reverse stress tests may be informed by science and modelling or expert opinion, or both, and often an assessment of probability will be estimated. Insurance regulators often focus on a 0.5 % probability level as a benchmark, i.e. the worse that may be expected every 200 years. If stress and scenario tests give numbers for an estimated 1 in 200 events that the stochastic model says could happen, say, every 10 years, then it casts doubt on the assumptions within the model or the test itself — they could be assessed and challenged. Similarly, the framing of multievent reverse stress tests may challenge assumptions about dependency and correlation within the model.

Realistically, deterministic methods are not 100 % reliable, taking as they do only a subset of potential events, but their practical performance in preventing hazard -impacting communities is as good and in some cases even better than other methods. If properly presented they can be clear, transparent and understandable. The process of developing deterministic stress and scenario sets can also be a means to engage a range of experts and stakeholders in the risk analysis process, gaining buy-in to the process.

Whether rules and standards derived from such tests work may depend on the risk culture of the region or firm where the risk is managed. Some risk cultures have a highly disciplined approach to rules, whereas others allow or apparently tolerate a degree of flexibility. Furthermore, the effort required to create, maintain and check for compliance where technical standards are concerned is considerable and may be beyond the capacity of those entrusted with enforcement.

2.1.3.3 Semi-quantitative risk analysis

Semi-quantitative risk analysis seeks to categorise risks by comparative scores rather than by explicit probability and financial or other measurable consequences. It is thus more rigorous than a purely qualitative approach but falls short of a full comprehensive quantitative risk analysis. But rather like deterministic methods, it can complement a full stochastic risk analysis by inserting a reality check. Semi-quantitative methods can be used to illustrate comparative risk and consequences in an accessible way to users of the information. Indeed, some output from complex stochastic models may be presented in forms similar to that used in semi-quantitative risk analysis, e.g., risk matrices and traffic light rating systems (for example where red is severe risk, orange is medium risk, yellow is low risk and green is very low risk).

Semi-quantitative risk analysis seeks to categorise risks by comparative scores rather than by explicit probability and financial or other measurable consequences.

A risk matrix is a means to communicate a semi-quantitative risk assessment: a combination of two dimensions of risk, severity and likelihood, which allows a simple visual comparison of different risks.

Severity can be considered for any unwanted consequence such as fire, explosion, toxic release, impact of natural hazards (e.g. floods and tsunamis) with their effects on workers and the community, environmental damage, property damage or asset loss. A severity scale from minor to catastrophic can be estimated or calculated, perhaps informed by some form of model. Normal risk matrices usually have between four and six levels of severity covering this range with a similar number of probability scales. There is no universally adopted set of descriptions for these levels, so stakeholders can make a logical selection based on the purpose of the risk assessment being carried out. The example depicted in Figure 2.2, below, is designed for risk assessment by a chemical production company and is based on effects on people. Similar matrices can be produced for environmental damage, property or capital loss. See also Chapter 2.5, Figure 2.21 for the risk matrix suggested by European Commission (2010).

In this illustrative example the severity scale is defined as:

- insignificant: minor injury quick recovery;
- minor: disabling injury;
- moderate: single fatality;
- major: 2 -10 fatalities;
- severe: more than 11 fatalities.

Similarly, the likelihood scale is defined as:

- rare: no globally reported event of this scale — all industries and technologies;
- unlikely: has occurred but not related to this industry sector;
- possible: has occurred in this company but not in this technology;
- likely: has occurred in this location — specific protection identified and applied;
- almost certain: has occurred in this location — no specific protection identified and applied.

When plotted in the matrix (Figure 2.2), a link may be provided to rank particular risks or to categorise them into tolerable (in green), intermediate (in yellow and orange) or intolerable (in red) bands. A risk which has severe consequences and is estimated to be 'likely' would clearly fall into the intolerable band. A risk which has minor consequences would be intermediate and 'very rare' in likelihood would be in the tolerable band. For risks which appear in the intolerable band, the user will need to decide what is done with the result.

There are choices to be made, either to reduce the severity of the consequence or the receptor vulnerability and/or to reduce the event's likelihood. All may require changes to the hazardous process. Many users would also require intermediate risks to be investigated and reduced if practicable.

Some users apply numerical values to the likelihood and/or severity axes of the matrix. This produces a 'calibrated' matrix.

The following matrix, in Figure 2.3 is derived from the Health and Safety Executive's publication Reducing risks, protecting people (2001) as well as from its final report on the

FIGURE 2.2

A risk matrix
Source: courtesy of authors

LIKELIHOOD	CONSEQUENCES				
	Insignificant	Minor	Moderate	Major	Severe
Almost Certain	M	H	H	E	E
Likely	M	M	H	H	E
Possible	L	M	M	H	E
Unlikely	L	M	M	M	H
Rare	L	L	M	M	H

Buncefield fire and explosion, Safety and environmental standards for fuel storage sites (2009).

Sometimes matrices are used to compare different risk types as per this example from the United Kingdom's National risk register of civil emergencies report (2015). Such matrices are intuitively attractive, but in practice they can be misleading (Cox, 2008).

Very often an assessment of both frequency and severity is highly subjective and so can greatly differ , even when produced by two people with similar experiences; the impact of expert judgement can be profound (Skjong and Wentworth, 2001). It is vital for reasoning to be given for any

FIGURE 2.3

A calibrated risk matrix
Source: Health and Safety Executive (2001, 2009)

FREQUENCY/ LIKELIHOOD		SINGLE FATALITY	2 - 10 FATALITIES	11 - 50 FATALITIES	51 - 100 FATALITIES	101+ FATALITIES
Likely	$>10^{-2}$/yr	Intolerable	Intolerable	Intolerable	Intolerable	Intolerable
Unlikely	$>10^{-4}$/yr but $<10^{-2}$/yr	Tolerable (but intolerable if individual risk of fatality $>10^{-3}$/yr)	Tolerable (but intolerable if individual risk of fatality $>10^{-3}$/yr)	Intolerable	Intolerable	Intolerable
Very unlikely	$>10^{-6}$/yr but $<10^{-4}$/yr	Tolerable	Tolerable	Tolerable	Tolerable	Intolerable
Remote	$>10^{-8}$/yr but $<10^{-6}$/yr	Broadly Acceptible	Broadly Acceptible	Tolerable	Tolerable	Tolerable

FIGURE 2.4

A comparative risk matrix
Source: United Kingdom Cabinet Office (2015)

OVERALL RELATIVE IMPACT SCORE	Between 1 in 20,000 and 1 in 2,000	Between 1 in 2,000 and 1 in 200	Between 1 in 200 and 1 in 20	Between 1 in 20 and 1 in 2	Greater than 1 in 2
5				Pandemic Influenza	
4			Coastal Flooding Widespread electricty failure		
3		Major transport accidents Major industrial accidents	Effusive volcanic eruptions Emerging infectuaous diseases Inland flooding	Severe space weather Low temperatures/heavy snow Heatwaves Poor air quality events	
2		Public disorder Severe wildfires	Animal diseases Drought	Explosive volcanic eruption Storms and gales	
1			Disruptive industrial action		

RELATIVE LIKELIHOOD OF OCCURING IN NEXT 5 YEARS assessment, therefore allowing debate and challenge.

If subject to a full probabilistic modelling exercise, we would not just have one value for coastal flooding but rather a complete distribution of coastal floods from frequent but very low severity to rare but very high severity.

Which point of the curve should be picked for each peril? Different selections will give very different impressions of comparative risk.

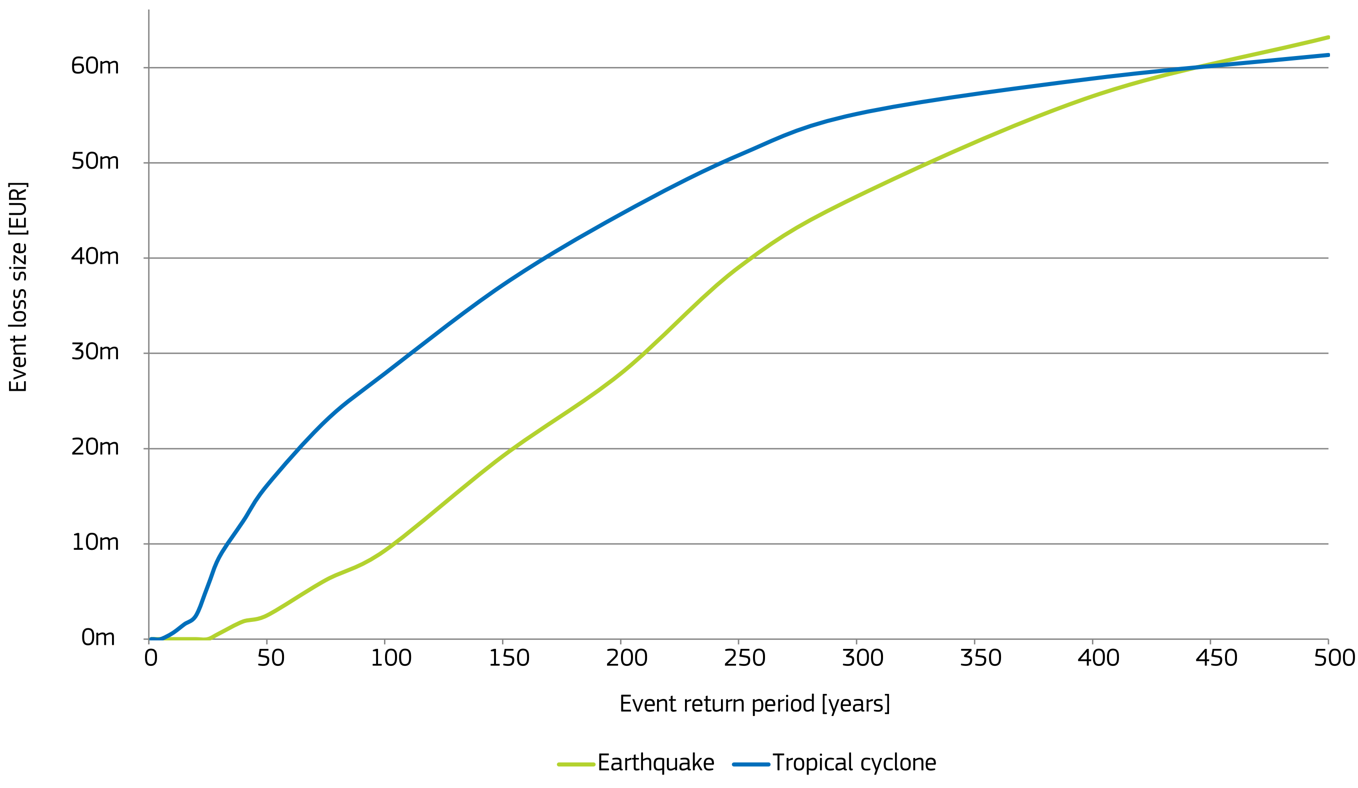
Semi-quantitative methods can be a useful stepping stone towards a full quantitative system, particularly where detailed data are lacking, and can be used as a means to capture subjective opinion and hold it up to challenge, opening debate and becoming a framework to identify where additional analytical effort is required.

2.1.3.4 Probabilistic risk analysis

This method originated in the Cold War nuclear arms race, later adopted by the civil nuclear industry. It typically attempts to associate probability distributions to frequency and severity elements of hazards and then run many thousands of simulated events or years in order to assess the likelihood of loss at different levels. The method is often called Monte Carlo modelling after the gaming tables of the principality's casinos. These methods have been widely adopted by the insurance industry, particularly where problems are too complicated to be represented by simple formulae, including catastrophic natural hazard risks.

FIGURE 2.5

Anonymised insurer comparative event exceedence curve
Source: Willis Towers Watson



A commonly used generic term for these methods is QRA or probabilistic or stochastic risk modelling. Today it is frequently used by industry and regulators to determine individual and societal risks from industries which present a severe hazard consequence to workers, the community and the environment. EU legislation such as the Seveso III directive (Directive 2012/18/EU) requires risks to be mapped and managed to a tolerable level. These industrial requirements have resulted in the emergence of organisations, specialists and consultants who typically use specially designed software models. The use of probabilistic methods is spreading from the industrial field to others, for example the Netherlands flood defence planning.

Probabilistic or stochastic risk analysis seeks to understand and model all potential events with their associated probabilities and outcomes, allowing a sophisticated cost/benefit analysis of different risk management strategies.

Stochastic risk modelling has been wholeheartedly embraced by the re/insurance industry over the past 30 years, particularly for natural catastrophes, though increasingly for all types of risks. EU solvency II regulation (Directive 2009/138/EC), a manifestation of the advisory insurance core principles for regulators set by the International Association of Insurance Supervisors in Basel (IAIS, 2015), allows companies to substitute some or all of their regulatory capital calculation with their own risk models if approved by their regulatory and subject to common European rules.

The main advantage of a quantitative method is that it considers frequency and severity together in a more comprehensive and complex way than other methods. The main problem is that it can be very difficult to obtain data on risks: hazard, exposure, vulnerability and consequential severity. If it is difficult to understand and represent the characteristics of a single risk then it is even harder to understand their interdependencies. There is inevitably a high level of subjectivity in the assumptions driving an 'objective' quantitative analysis. A paper by Apostolakis (2004) on QRA gives a coherent argument for appropriate review and critique of model assumptions. The level of uncertainty inherent in the model may not always be apparent or appreciated by the ultimate user, but the results of a fully quantitative analysis, if properly presented, enhance risk understanding for all stakeholders.

Often the process of building a probabilistic model is as valuable as the results of the model, forcing a structured view of what is known, unknown and uncertain and bringing assumptions that may otherwise be unspoken into the open and thereby challenging them.

Typically for a full stochastic model, severities for each peril would be compared for different probability levels, often expressed as a return period; the inverse of annual probability, i.e. how many years would be expected to pass before a loss of a given size occurred.

Figure 5 gives an example of output of such a model, here showing the size of individual loss for two different perils with return periods of up to the worst that may be expected every 500 years. Note that a return period is a commonly used form of probability notation. A 1-in-200 year loss is the worst loss that can be expected every 200 years, i.e. a loss with a return period of 200 years. A return period is the inverse of probability; a 1- in -200 year event has a 0.5 % probability (1/200).

We can see that, for example, every 100 years the worst tropical cyclone loss we can expect is over EUR 28 million compared to the worst earthquake loss we can expect every 100 years of EUR 10 million.

In fact, a tropical cyclone gives rise to significantly higher economic loss than an earthquake, up until the 1 -in-450-year probability level. But which is the most dangerous? A more likely event probabilities tropical cyclone is much more damaging, but at very remote probabilities it is earthquake. Notice too the very significant differences in loss estimate for the probability buckets used in the National risk register for civil emergencies report (United Kingdom Cabinet Office 2015) risk matrix example in Figure 2.4. The national risk register looks at the probability of an event occurring in a 5-year period, but compares the 1-in-40-year loss to the 1-in-400-year loss, broadly equivalent to the 1-in-200 to 1-in-2 000 5-year bucket: the loss for both perils at these probability levels is very different.

Terms like '1-in-100 storm' or '1-in-100 flood' are often used in the popular press, but it is important to define what is meant by these terms. Is this the worst flood that can be expected every 100 years in that town, valley, region or country? It is also important not just to look at the probability of single events as per Figure 2.5, an occurrence exceedance probability curve, but also annual aggregate loss from hazards of that type, i.e. an annual aggregate exceedance probability curve. For a given return period the aggregate exceedance probability value will clearly be greater or at least equal to the occurrence exceedance probability — the 1 in 200 worst aggregate exceedance probability could be a year of one mega event or a year of five smaller ones that are individually unexceptional but cumulatively significant.

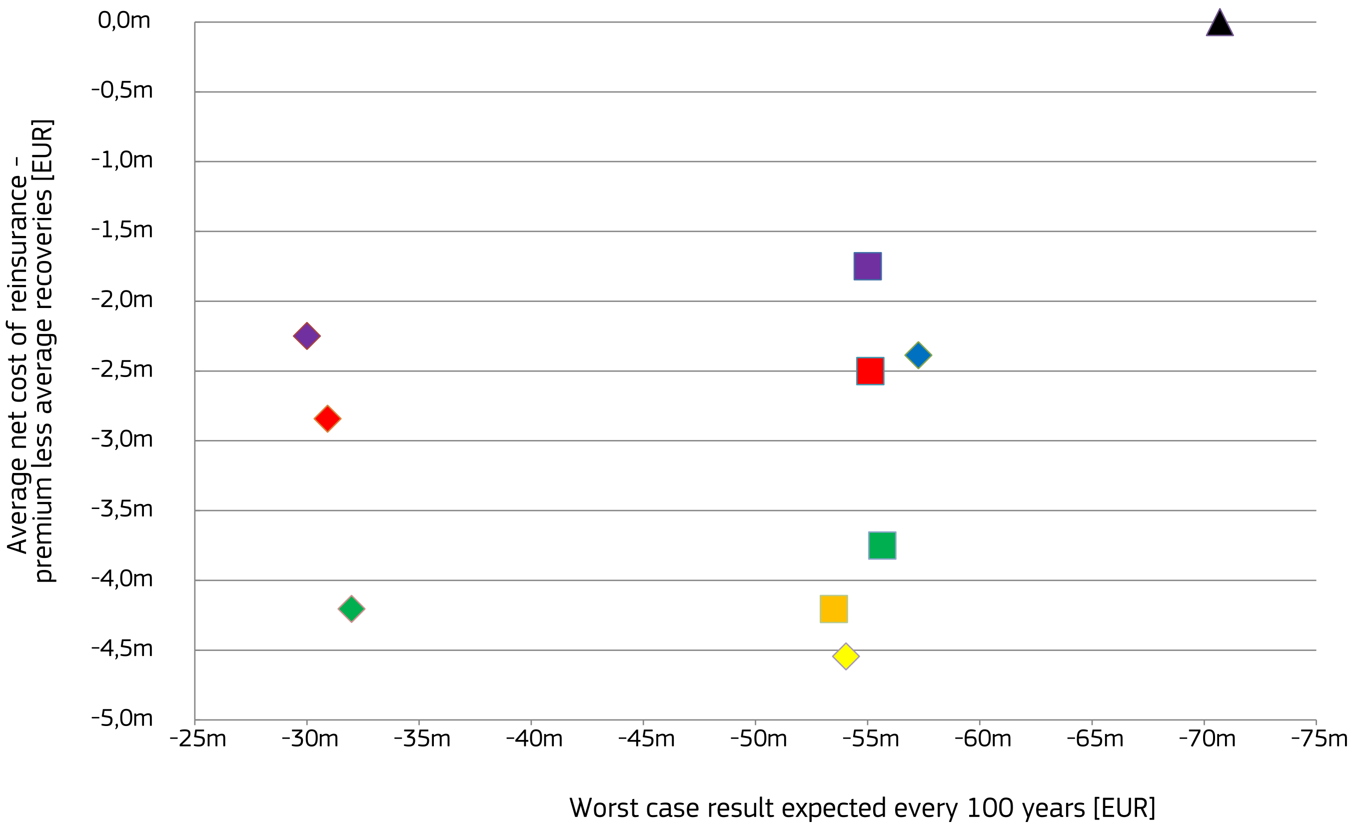
The models can be used to compare the outcome of different strategies to manage and mitigate risk. The cost and benefit of different solutions can be compared, and so an optimal strategy rationalised. An anonymised insurance example is shown in Figure 2.6.

Figure 2.6 compares 10 reinsurance hedging options to manage insurance risk against two measures, one of risk and one of return. On the horizontal axis we have the risk measure: the worse result that we may expect every 100 years, while on the vertical axis we have the return measure, or rather its inverse here, the cost of each hedging option.

Ideally we would be to the top left

FIGURE 2.6

An anonymised example of a risk return analysis
Source: Willis Towers Watson



of the chart: low risk but low cost. The 'do nothing' option is the black triangle at the top right: high risk (a EUR 70 million 1-in-100 year loss) but zero additional cost. The nine re-insurance hedging options fall into two clusters on the chart.

The purple diamond option to the extreme left has the least risk, reducing the 1-in-100 loss to EUR 30 million, but at an annual cost of EUR 2.25 million. The other two options in that cluster cost more and offer less benefit so can be ignored. The best opinion of the middle group is the purple square, reducing the 1-in-100 loss to EUR 55 million but at an annual average cost of EUR 1.75 million. Again, this option clearly offers the best risk return characteristics of all the others in the middle group, so the others in that group may be discounted.

Therefore, from 10 options including the 'do nothing', option we have a shortlist of three:

- black triangle: high risk (EUR 70 million 1-in-100 loss), zero cost;
- purple square: medium risk (EUR 55 million 1-in-100 loss), medium cost (EUR1.75million);
- purple diamond: lowest risk (EUR 30 million 1-in-100 loss), highest cost (EUR2.25million).

Which to pick depends on the risk appetite of the firm. If they are uncomfortable with the unhedged risk then the purple diamond seems to offer much better protection than the purple square option for comparatively little additional cost.

Similar methods can be used to compare options for, say, managing flood risk in a particular location and/or process risk for a particular plant. The same metrics can be used to look at and compare different perils and combinations of perils. The methods make no moral judgements but allowing the cost of a particular strategy to be compared against the reduction is a risk as defined by a specific risk measure. It is at this point that more subjective, political decisions can be made on an informed, objective basis.

An example of a comparative peril analysis for a European city is outlined in a paper by Grünthal et al. (2006) on the city of Cologne.

It must always be remembered that models advise, not decide. Such charts and analyses should not be considered definitive assessments; like any model they are based upon a set of defined assumptions.

2.1.4 Conclusions and key messages

Partnership

The process of risk assessment acts as a catalyst to improve risk understanding and so to encourage a process of proactive risk management. An early adapter of these methods, the global catastrophe insurance and reinsurance industry has been transformed by the process and has become more technically adept, more engaged with science and more financially secure, providing more resilience for society. Similarly, the manufacturing and process industries have embraced structured risk identification and assessment techniques to improve the safety of the manufacturing process and the safety of the consumer.

Disaster risk assessment requires a combination of skills, knowledge and data that will not be held within one firm, one industry, one institution, one discipline, one country, or necessarily one region. Risk assessment requires input from a variety of experts in order to identify potential hazards, those that could occur as well as those in the historical record.

Rigorous approaches to risk assessment require scientific modelling and a precise understanding of risk and probability. Scientific models can be compared in order to challenge the underlying assumptions of each and lead to better, more transparent decisions.

As risk assessments get more quantitative, scientific, and technical, it is important that policymakers are able to interpret them. The assumptions within models must be transparent, and qualitative risk assessment (such as deterministic scenario impacts or risk matrixes) can be useful and complementary to stochastic modelling. It is important that policymakers can demonstrate that appropriate expertise and rigor has been engaged to found risk management decisions firmly.

The practitioner lies in the centre of the many opportunities for partnerships in disaster risk assessment. In order to think beyond accepted ways of working and challenge ingrained assumptions, links between other practitioners in familiar fields as well as other sectors and industries and academia are extremely valuable.

Knowledge

The risk assessment process is structured and covers risk identification, hazard assessment, determining exposure and understanding vulnerability.

Depending on the objective of risk assessment and data availability, risk assessment methods can range in formalization and rigor. There are more subjective scenario based deterministic models, semi quantitative risk analyses such as risk matrixes, and fully quantitative risk assessment; probabilistic or stochastic risk modelling. The more qualitative approaches to risk add value through the process of developing a framework to capture subjective risk perception and serve as a starting point for a discussion about assumptions and risk recognition engaging a wide variety of experts and stakeholders in the process. They also provide a means to reality check more theoretical models. Probabilistic and stochastic analyses provide the potential to perform cost/benefit or risk/return analysis, creating an objective basis for decision making.

Rigorous quantitative approaches to risk assessment and probabilistic analysis raise awareness of the need for further scientific input and the requirement to transfer of knowledge and engagement between science and practitioners.

Risk assessment and analysis provides a framework to weigh decisions, and risk models provide an objective basis against which policy decisions can be made and justified. However, it is important that the limitations of modelling are recognized and inherent uncertainty is understood. Having the ability to compare and challenge assumptions, as well as requiring evidence based analysis, is required.

Risk perception is subjective, but practitioners have valuable information in the fields of data, methodologies and models that further solidify frameworks through which hazards can be understood and compared in an objective fashion.

Innovation

Innovation is required to meet the challenges of lack of data and partial information in risk identification and modelling. Creative approaches can be made to capture and challenges assumptions implicitly or explicitly made and so test them against available data and defined stresses.

Risk analysis creates a framework; a starting point for debate about policy, risk and what we know and cannot know. This leads to greater understanding and better, more transparent decision-making.

No model is perfect. New scientific input can improve and challenge models – testing sensitivity to prior assumption, so leading to a greater understanding of disaster events which in turn leads to safer companies, communities and countries A deeper understanding of the quantitative and qualitative approaches to risk management can help innovate ways of thinking about subjective public risk perception, and risk assessment frameworks can develop a more objective understanding of risk and risk-informed decision making.

Risk assessment and associated modelling contain inherent uncertainty and are not fully complete. It is important to innovate in areas where hazards are less known and capable of anticipation; truly "unknown unknowns" and "known unknowns" must be considered. Similarly assumptions held for "known knowns" should be continuously challenged and tested as new information arises.

2.2 Current and innovative methods to define exposure

***Christina Corbane**, Paolo Gamba, Martino Pesaresi, Massimiliano Pittore, Marc Wieland*

2.2.1 What is exposure?

Exposure with vulnerability (see Chapter 2.3) and hazard (see Chapter 3) is used to measure disaster risk (see Chapter 2.3). It is reported that exposure has been trending upwards over the past several decades, resulting in an overall increase in risk observed worldwide, and that trends need to be better quantified to be able to address risk reduction measures. Particular attention to understanding exposure is required for the formulation of policies and actions to reduce disaster risk (UNISDR, 2015a), as highlighted by the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015b): 'Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be leveraged for the purpose of pre -disaster risk assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters.

Exposure is a necessary, but not sufficient, determinant of risk (Cardona et al., 2012) (see Chapter 2.1). According to available global statistics, least developed countries represent 11 % of the population exposed to hazards but account for 53 % of casualties, while the most developed countries account for 1.8 % of all victims (Peduzzi et al., 2009) with a population exposure of 15 %. These figures show that similar exposures with contrasting levels of development, of land- use planning and of mitigation measures lead to drastically different tolls of casualties. Hence it is possible to be exposed, but not vulnerable; however, it is necessary to also be exposed to be vulnerable to an extreme event (Cardona et al., 2012).

Due to its multidimensional nature, exposure is highly dynamic, varying across spatial and temporal scales: depending on the spatial basic units at which the risk assessment is performed, exposure can be characterised at different spatial scales (e.g. at the level of individual buildings or administrative units).

Exposure represents the people and assets at risk of potential loss or that may suffer damage to hazard impact. It covers several dimensions like the physical (e.g. building stock and infrastructure), the social (e.g. humans and communities) and the economic dimensions.

Population demographic and mobility, economic development and structural changes in the society transform exposure over time. The quantification of exposure is challenging because of its interdependent and dynamic dimensions. The tools and methods for defining exposure need to consider the dynamic nature of exposure, which evolves over time as a result of often unplanned urbanisation, demographic changes, modifications in building practice and other socioeconomic, institutional and environmental factors (World Bank, GFDRR, 2014). Various alternative or complementary tools and methods are followed to collect exposure-related data; they include rolling census and digital in situ field surveys. When the amount, spatial coverage and/or quality of the information collected in the ground is insufficient for populating exposure databases, the common practice is then to infer characteristics on exposed assets from several indicators, called proxies. Exposure modelling also has a key role to play in risk assessment, especially for large- scale disaster risk models (regional to global risk modelling (De Bono and Chatenoux, 2015; De Bono and Mora ,2014)). Among the different tools for collecting information on exposure, Earth observation represents an invaluable source of up-to-date information on the extent and nature of the built-up environments, ranging from the city level (using very high spatial resolution data) to the global level (using global coverage of satellite data) (Deichmann et al., 2011; Dell'Acqua et al. ,2013; Ehrlich and Tenerelli, 2013). Besides, change -detection techniques based on satellite images can provide timely information about changes to the built-up environment (Bouziani et al., 2010).The choice of the approach determines the resolution (spatial detail) and the extent (spatial coverage) of the collected exposure data. It also influences the quality of the collected information.

Despite the general conceptual and theoretical understanding of disaster exposure and the drivers for its dynamic variability, few countries have developed multihazard exposure databases to support policy formulation and disaster risk- reduction research. Existing exposure databases are often hazard specific (earthquakes, floods and cyclones), sector specific (infrastructure and economic) or target specific (social, ecosystems and cultural) (Basher et al., 2015). They are often static, offering one-time views of the baseline situation, and cannot be easily integrated with vulnerability analysis.

This chapter reviews the current initiatives for defining and mapping exposure at the EU and global levels. It places emphasis on remote sensing-based products developed for physical and population exposure mapping. Innovative approaches based on probabilistic models for generating dynamic exposure databases are also presented together with a number of concrete recommendations for priority areas in exposure research. The broader aspects of exposure, including environment (e.g. ecosystem services) and agriculture (e.g. crops, supply chains and infrastructures), deserve to be addressed in a dedicated future chapter and will not be covered by the current review.

2.2.2 Why do we need exposure?

There is a high demand for exposure data by the communities that address disaster risk reduction (DRR). National governments and local authorities need to implement DRR programmes; the insurance community needs to set premiums and manage their aggregate exposures; civil society and the aid community need to identify the regions of the world that most urgently require DRR measures (Ehrlich and Tenerelli, 2013). Effective adaptation and disaster risk management (DRM) strategies and practices depend on a rigorous understanding of the dimensions of exposure (i.e. physical and economic) as well as a proper assessment of changes and uncertainties in those dimensions (Cardona et al., 2012).

Both the scope and the scale of the natural hazard impact assessment determine the type of exposure data to be collected.

Risk models require detailed exposure data (e.g. with information on buildings, roads and other public assets) to produce as outputs risk metrics such as the annual expected loss and the probable maximum loss (see Chapter 2.4). For instance, catastrophe models commonly used by the insurance industry include an exposure module, which represents either a building of specific interest, a dwelling representative of the average construction type in a given area or an entire portfolio of buildings with different characteristics (e.g. an entire city). The characteristics may include physical characteristics like building height, occupancy rate, usage (private, public like commercial, industrial, etc.), construction type (e.g. wood or concrete) and age, and also non-physical characteristics like the replacement cost which is needed for calculating the loss at a certain location (Michel-Kerjan et al., 2013). Besides, insurance companies need to assess and model the business interruption that represents a major part of the total economic loss. To quantify loss due to business interruption, exposure databases need to include information on building contents and business information for different types of properties (Rose and Huyck 2016). These industry exposure databases are often proprietary and use heterogeneous taxonomies and classification systems which hinder efforts of merging independently developed datasets (GFDRR, 2014). However, the Oasis (OASIS, 2016) community and the recently established Insurance Development Forum are dedicating special efforts to exposure data harmonisation, sourcing, structuring and maintenance at the global levels. Moreover, an initiative lead by Perils is offering de facto standard industry exposure databases for property across Europe at an aggregated spatial level (PERILS, 2016).

If the aim is to know whether a particular feature is likely to be affected or not by a certain level of hazard, then it is enough to simply identify the location of that feature (e.g. building location and building footprint) or group of features (e.g. building stock). Whereas if the purpose is to understand the potential economic impacts or human loss, then other attributes of the feature or group of features need to described (e.g. the type of construction materials, population density and the replacement value). Exposure databases detailed to single building units are seldom available for disaster modellers. Instead, the exposure data are more often available in an aggregated level for larger spatial units related to arbitrary areal subdivision of the settlements, census block, postal codes, city blocks or more regular gridded subdivision. A spatial unit may contain a statistic summary of building information such as average size and average height, density or even relative distribution of building types (Ehrlich and Tenerelli, 2013). For optimal results the choice of the attribute and its granularity should be aligned with the scale and the purpose of the risk assessment. To a certain extent, the requirements in terms of granularity also depend on the peril being modelled: e.g. flood models require detailed information on the location and building type. By contrast, windstorm models arguably need to be less precise. Detailed gust speeds will not be known at a precise location level but rather estimated on a broader spatial scale. There are clearly many attributes that can be attached to exposure data. Developing such databases requires a multidisciplinary team of construction engineers, economists, demographers and statisticians.

In recent years, several exposure datasets with regional or global coverage have attempted to generate detailed building inventories and compile exposure data despite the challenges related to the heterogeneous mapping schemas, the different typologies and the varying resolutions. In the following sections, we review the existing initiatives at EU and global levels that have made a first step in overcoming these obstacles either i) by using exposure proxies such as land -use and land- cover products, ii) by using Earth observation technologies for mapping human settlements and population or iii) by integrating existing information from different acquisition techniques, scales and accuracies for characterising the assets at risk and for describing the building stock. We purposely limit the review here to large -scale exposure datasets that have a spatial component (i.e. associated with a geographic location) and that are open, hence ensuring replicability and a better understanding of risk (World Bank, 2014).

2.2.3 Land-cover and land-use products as proxies to exposure

These products outline areas with different uses, including ‘industrial’, ‘commercial’ and ‘residential’ classes, as well as non-impervious areas (e.g. green spaces).

Land- use and land-cover (LU/LC) information products that are usually derived from remote sensing data may provide information on buildings and thus on exposure.

Some products may also describe the building density. LU/LC maps provide valuable information on infrastructure such as roads. The spatial characteristics of LU/LC maps are influenced by the minimum mapping units , which refer to the smallest size area entity to be mapped.

2.2.3.1 European land-use and land-cover (LU/LC) products

The currently available EU-wide and global LU/LC products have minimum mapping units ranging between 0.01 ha (e.g. the European Settlement Map (ESM)) to 100 ha (e.g. MODIS land cover). At the EU level, the Corine Land Cover is the only harmonised European land cover data available since 1990. It comprises 44 thematic classes with units of 25 ha and 5 ha for changes, respectively. From 1990 until 2012, four of such inventories were produced and completed by change layers, and it has been used for several applications like indicator development, LU/LC change analysis (Manakos and Braun, 2014) and flood risk assessment within the EU context (Lugeri et al., 2010). However, its limitations in terms of spatial resolution do not allow the conversion of land- cover classes into accurate, physical exposure maps. To complement LU/LC maps, detailed inventories of infrastructures are essential for assessing risks to infrastructures as well as for managing emergency situations. In 2015, a geographical

FIGURE 2.7

European Settlement Map– 10 m resolution – Genova
Source: European Commission (JRC)

database of infrastructure in Europe was developed including transport networks, power plants and industry locations. (Marin Herrera et al., 2015). The database was successfully used in a comprehensive multihazard and multisector risk assessment for Europe under climate change (Forzieri et al., 2015).

The Urban Atlas is another pan-European LU/LC product describing, in a consistent way, all major European cities' agglomerations with more than 100 000 inhabitants. The current specifications of the Urban Atlas fulfil the condition of a minimum mapping unit of 0.25 ha, allowing the capture of urban, built-up areas in sufficient thematic and geographic detail (Montero et al., 2014). The Urban Atlas cities are mapped in 20 classes, of which 17 are urban classes. It is a major initiative dealing with the monitoring of urban sprawl in Europe, designed to capture urban land use, including low- density urban fabric, and in this way it offers a far more accurate picture of exposure in urban landscapes than the Corine Land Cover does. Despite its accuracy and relevance for risk modelling, the main limitation of this product is its spatial coverage, as it is restricted to large urban zones and their surroundings (more than 100 000 inhabitants).

Currently, the continental map of built-up areas with the highest resolution so far produced is the ESM (Florczyk et al., 2016). The ESM (Figure 2.7) is a 10 metre x 10 metre raster map expressing the proportion of the remote sensing image pixel area covered by buildings; it was produced in 2013-2014. It was developed jointly by two services of European Commission (JRC and REGIO). The ESM is distributed as a building density product at both 10 metre x 10 metre and 100 metre x 100 metre resolutions, each supporting specific types of applications. For a pan-European risk assessment (Haque et al. 2016), the coarser (100 metre) resolution is sufficient, whereas the 10 metre product would be necessary for local to regional risk assessment.

2.2.3.2 Global land-use and land-cover products

A number of global land- cover products covering different time periods and different spatial resolutions have been created from remote sensing, e.g. MODIS (Friedl et al., 2010), Africover, GLC-SHARE of 2014 (Latham et al., 2014), GLC2000 (Fritz et al., 2010), IGBP (Loveland et al., 2000) and GlobCover (Arino et al., 2012). Many of these products are based on coarse resolution sensors, e.g. GLC2000 is at 1 km, MODIS is at 500 metre and GlobCover is at 300 metre resolution, which hampers the potential to provide accurate exposure data that can directly feed into risk assessment models.

The first high- resolution (30 metres) global land -cover product is the GlobeLand30, which comprises 10 types of land cover including artificial surfaces for years 2000 and 2010 (Chen et al., 2015). However, the 'artificial surfaces' class consists of urban areas, roads, rural cottages and mines impeding the straightforward conversion of the data into physical exposure maps.

The Global Urban Footprint describing built-up areas is being developed by the German Aerospace Centre and is based on the analysis of radar and optical satellite data. The project intends to cover the extent of the large urbanised areas of megacities for four -time slices: 1975, 1990, 2000 and 2010 at a spatial resolution of 12 metre x 12 metre (Esch et al., 2012). Once available, this dataset will allow effective comparative analyses of urban risks and their dynamics among different regions of the world.

The global human settlement layer (GHSL) is the first global, fine- scale, multitemporal, open data on the physical characteristics of human settlements. It was produced in the framework of the GHSL project, which is supported by the European Commission. The data have been released on the JRC open data catalogue (Global Human Settlement Layer, 2016). The main product, GHS Built-up, is a multitemporal built-up grid (built-up classes: 1975, 1990, 2000 and 2014), which has been produced at high resolution (approximately 38 metre x 38 metre). The GHS Built-up grid was obtained from the processing of the global Landsat archived data in the last 40 years in order to understand global human settlement evolution. The target information collected by the GHSL project is the built-up structure or building aggregated in built-up areas and then settlements according to explicit spatial composition laws. They are the primary sign and empirical evidences of human presence on the global surface that are observable by current remote sensing platforms. As opposed to standard remote sensing practices based on urban land cover or impervious surface notions, the GHSL semantic approach is continuously quantitative and centred around the presence of buildings and their spatial patterns (Pesaresi et al., 2015; Pesaresi et al., 2013). This makes the GHSL perfectly suitable for describing the physical exposure and its changes over time at a fine spatial resolution (Pesaresi et al., 2016).

2.2.4 Status of population exposure at the EU and global levels

The static component relates to the number of inhabitants per mapping unit and their characteristics, whereas the dynamic component refers to their demography and their activity patterns that highlight the movement of population through space and time. Population distribution can be expressed as either the absolute number of people per mapping unit or as population density. Census data are commonly used for enumerating population and for making projections concerning population growth. Census data may also contain other relevant characteristics that are used in risk assessment, such as information on age, gender, income, education and migration.

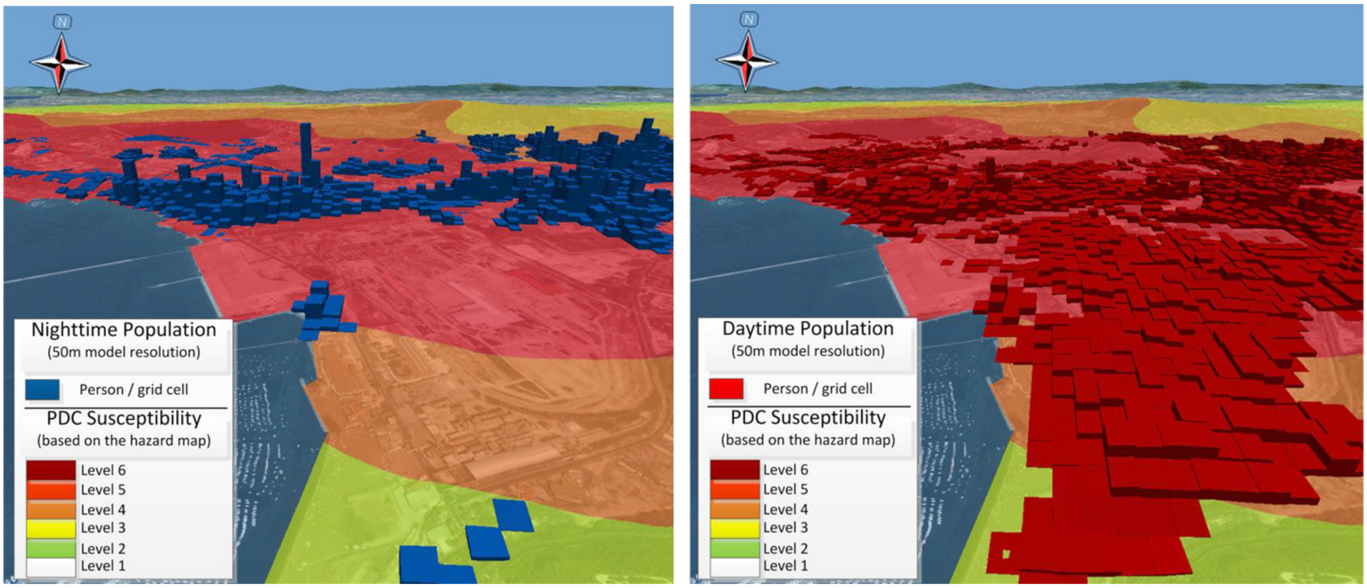
For large- scale analysis, census data are costly and seldom available in large parts of the world or are even outdated or unreliable. Remote sensing, combined with dasymetric mapping, represents an interesting alternative for large- scale mapping of human exposure. Dasymetric mapping consists in disaggregating population figures reported at coarse source zones into a finer set of zones using ancillary geographical data like LU/LC.

2.2.4.1 European-wide population grids

At the EU level, a European population grid with a spatial resolution of 100 metres x 100 metres was produced (Batista e Silva et al., 2013). The method involved dasymetric mapping techniques with a resident population reported at the commune level for the year 2011 and a refined version of the Corine Land Cover as the main input sources. The data are publically distributed on the geographic information system of the Commission following the standardised 1 km x 1 km grid net and the Inspire specifications. A new population grid at 10 me-

FIGURE 2.8

Modeled nighttime and daytime population densities (at 50 m) and volcanic hazard zones in Campi Flegrei – Naples.
Source: Sergio Freire et al. (2015)



tres has recently been produced for the whole European territory, which builds on the ESM at 10 metres as a proxy of the distribution of residential population and 2011 census data (Freire et al., 2015a). The layer has been produced upon request of the European Commission and will soon be made freely available and downloadable online. Figure 2.8. shows an example of potential uses of the 10 -metre- resolution, EU- wide ESM map for modelling day and night population distribution in volcanic risk assessment.

2.2.4.2 Global human exposure

Global distribution of population in terms of counts or density per unit area is considered as the primary source of information for exposure assessment (Pittore et al., 2016). Global population data are available from the LandScan Global Population Database (Dobson et al., 2000), which provides information on the average population over 24 hours and in a 1 km resolution grid.

The LandScan data have annual updates and are widely used despite being a commercial product. Although LandScan is reproduced annually and the methods are constantly revised, the annual improvements made to the model and the underlying spatial variables advise against any comparison of versions.

Other global human exposure datasets include the Gridded Population of the World (GPWv4) available at a resolution of approximately 5 km at the equator. It is developed by SEDAC and provides population data estimates at a spatial resolution of approximately 1 km at the equator. For GPWv4 , population input data are collected at the most detailed spatial resolution available from the results of the 2010 round of censuses, which occurred between 2005 and 2014. The input data are extrapolated

FIGURE 2.9

Global human exposure represented by the GHSL population data in 3D. The box represents an example of application for analysing the evolution of exposure to coastal hazards over the last 40 years.
Source: Pesaresi et al. (2016)

to produce population estimates for the years 2000, 2005, 2010, 2015, and 2020 (Neumann et al., 2015).

The open WorldPop is another initiative providing estimated population counts at a spatial resolution of 100 metres x 100 metres through the integration of census surveys, high- resolution maps and satellite data (Lloyd et al., 2017) . Within the WorldPop project, population counts and densities are being produced for 2000-2020; the available data currently essentially cover America, Asia and Africa.

People present the most important elements-at-risk with a static and dynamic component.

Recently, within the framework of the GHSL, an improved global layer called GHS-POP, which maps the distribution of the population with unprecedented spatio-temporal coverage and detail, has been released. The data have been produced from the best available global built-up layer (GHS-BU) and from census geospatial data derived from GPWv4. The population grids correspond to residential-based population estimates in built-up areas and not 'residential population' or 'population in their place of residence', for which consideration of land use would be required (Freire et al., 2015b).

The multitemporal data are available free of charge at a spatial resolution of 250 metres x 250 metres for 1975, 1990, 2000 and 2015. It has already successfully been used in the context of global risk assessment for the analysis of the increase in population exposure to coastal hazards over the last 40 years (Pesaresi et al., 2016).

2.2.5 Exposure data describing the building stock

Several exposure databases attempt to characterise the assets at risk by including physical exposure information. The latter is often derived from the integration of a large variety of possible exposure information sources using different modelling approaches. We review here the existing initiatives that describe the building stock through a variety of attributes (e.g. height, construction material and replacement value).

2.2.5.1 EU-wide building inventory databases

The European Union's seventh framework programme for research and technological development (FP7) project, the NERA (Network of European Research Infrastructure for Earthquake Risk Assessment and Mitigation) initiated the development of a European building inventory database to feed into the Global Exposure Database (GED) (see Chapter 2.2.5.2). The database builds upon the outcomes of NERIES project (Network of Research Infrastructures for European Seismology) to compile building inventory data for many European countries and Turkey (Erdik et al., 2010). The European building inventory is a database that describes the number and area of different European building typologies within each cell of a grid, with a resolution of at least 30 arc seconds (approximately 1 km2 at the equator) for use in the seismic risk assessment of European buildings (Crowley et al., 2012). The database includes building/dwelling counts and a number of attributes that are compatible with the Global earthquake model's basic building taxonomy (i.e. material, lateral load, number of storeys, date of construction, structural irregularity, occupancy class, etc.). This inventory contains useful information for the assessment of risk assessment and for the estimation of economic loss at the EU level.

2.2.5.2 Global building inventory databases

The prompt assessment of global earthquakes for response (PAGER) (Jaiswal et al., 2010), the GED for GAR 2013 (GEG-2013) and the GED for the Global earthquake model (GED4GEM) are examples of global exposure databases that specifically include physical exposure information.

On a country-by-country level, the PAGER (Jaiswal et al., 2010) contains estimates of the distribution of building types categorised by material, lateral force resisting system and occupancy type (residential or non-residential, urban or rural). The database draws on and harmonises numerous sources: (1) United Nations statistics, (2) the United Nations habitat's demographic and health survey database, (3) national housing censuses,

(4) the world housing encyclopaedia project and (5) other literature. PAGER provides a powerful basis for inferring structural types globally. The database is freely available for public use, subject to peer review, scrutiny and open enhancement.

The GEC-2013 (De Bono and Chatenoux, 2015) is a global exposure dataset at 5 km spatial resolution which integrates population and country-specific building typology, use and value. It has been developed for the global risk assessment 2013 with the primary aim of assessing the risk of economic loss as a consequence of natural hazards at a global scale. The development of GEG-2013 is based on a top-down or 'downscaling' approach, where information including socioeconomic, building type and capital stock at a national scale are transposed onto a regular grid, using geographic population and gross domestic product distribution models as proxies. GEG-2013 is limited in some important ways: i) it was fundamentally constructed using national indicators that were successively disaggregated onto a 5 × 5 km grid; and ii) the capital stock in each cell is distributed on the basis of the number of persons living in that cell and does not take into account the real value of the assets of the cell. The data can be downloaded from the GAR risk data platform.

The GED4GEM is a spatial inventory of exposed assets for the purposes of catastrophe modelling and loss estimation (Dell'Acqua et al., 2013, Gamba et al., 2012). It provides information about two main assets at risk: residential population and residential buildings. Potentially, it can also include information about non-residential population and buildings, although the amount of information for these two additional assets is currently quite limited. In general, the GED is divided into four different levels, which are populated from different data sources and use different techniques. Each level has a different geographical scale as for the statistical consistency of the data it contains as well as a different level of completeness. Each level is thus appropriate for a different use:

- Level 0 — A representation of the population and buildings on a 30-arc seconds grid with information about the buildings coming from statistics available at the country level. The building distribution is thus the same for each element of the grid belonging to a given country, with a binary difference between 'rural' and 'urban' areas.

- Level 1 — A representation of population and buildings on a 30 -arc seconds grid with information about the buildings that is available using the subnational statistics (e.g. for regions, states, provinces or municipalities according to the different countries).

- Level 2 — A representation where each element of the same 30 -arc seconds grid includes enough information to be consistent by itself, and no distribution on a bigger geographical scale is used. This case corresponds to the situation when all building counts are actually obtained, not by means of a disaggregation of a distribution available on a wider area on the elements of the grid but by aggregating building -level data, possibly available for the area of interest.

- Level 3 — A representation at the single building level, including all the possible information about each building, such as structural, occupancy and economic variables.

The first version of the GED contains aggregate information on population and the number/built area/reconstruction cost of residential and non-residential buildings at a 1 km resolution. Detailed datasets on single buildings are available for a selected number of areas and will increase over time.

2.2.6 Future trends in exposure mapping: towards a dynamic exposure modelling

The review of existing initiatives for defining and mapping exposure shows that there is a clear trend towards the use of satellite data in combination with statistical modelling (top-down and bottom-up approaches) for building exposure data: remotely sensed data sourcing for exposure is particularly useful in low-income and emerging economies which lack well-established data collection resources, frameworks and agencies. These economies are often also undergoing rapid urbanisation with dramatically changing exposure concentrations over short periods of time.

In parallel, over the last 5 years, the field of risk assessment has been increasingly driven by open data and open -source modelling, as highlighted in the report Understanding risk in an evolving world (GFDRR, 2014).

Open data initiatives such as the Humanitarian OpenStreetMap Team has contributed significantly to the collection of exposure data in vulnerable countries: in a little over a year, more than 160 000 individual buildings were mapped through crowdsourcing and in situ surveys.

At present, one of the most challenging aspects of exposure modelling is to implement multihazard exposure models through dynamic, scalable frameworks. The dynamic nature of such frameworks in this context reflects the need to explicitly account for both the time variability of the exposed assets and the constant evolution of their representation in the model, which is seldom complete and exhaustive.

Remote sensing, combined with dynamic exposure modelling and bottom-up approaches such as citizen mapping initiatives, can be an effective way to build large exposure databases .

In a dynamic, multiresolution exposure model, two basic types of entities should therefore coexist: atomic data and statistical (aggregated) models. Atomic data refer to physical structures such as buildings or bridges that have been analysed individually and possibly not fully enumerated. Statistical models are aggregated descriptions defined over specific geographic boundaries and possibly influenced by atomic data. Atomic data and statistical models are closely related and mutually interactive, with both having geometric properties and attributes. Compound models accommodating both atomic data and statistical models would be able to optimally exploit direct, in situ information obtained from specialised surveys, even if not complete and exhaustive, by constraining a set of statistical distributions describing the assets' attributes at the atomic level (e.g. material properties for a single building) or at the aggregation boundary level (for instance the expected number of storeys of different building types based on empirical observations in a city district). At atomic level, this can be obtained for instance by modelling the (in)dependence relationships among different assets' attributes and with external covariates (e.g. geographical location, altitude, terrain slope, etc.).

An example for a probabilistic information integration approach is given in Pittore and Wieland (2013), where Bayesian networks are proposed for their sound treatment of uncertainties and for the possibility of seamless merging of different data sources, including legacy data, expert judgement and data mining- based inferences. Due to the increasingly large variety of possible exposure information sources including sparse and incomplete data available at small- scale resolution, the issue of the need for the flexible integration of existing information at different scales and accuracies in order not to discard available information needs to be confronted.

To exploit the full capabilities of the available information in combined spatio-temporal approaches, a database is needed that allows one to model and query complex data types composed of multiple spatial and temporal dimensions. Information extracted from a satellite image or manually sampled in situ show different degrees of quality in terms of reliability and accuracy. Therefore, a probabilistic framework for information integration, updating and refinement is required, as exemplified in Pittore and Wieland (2013). During monitoring activities, the resulting information model continuously evolves and a dynamic exposure database should be able to track an object's evolution over space and time while accounting for its identity which is the lifespan of an object. To this regard, Pittore et al. (2015) propose a novel approach to prioritise exposure data collection based on available information and additional constraints. They utilise the concept of focus maps (Pittore, 2015), which combine different information layers into a single raster representing the probability of the point being selected for surveying, conditional on the sampling probability of each of the other layers. Based on a focus map, a set of sampling points is generated and suitably routed on the existing road network. This allows one to realise a further optimisation of the overall data collection by including additional survey constraints in the routing algorithm and which drives the in situ data collection phase. Iteratively repeating this process allows for an efficient model updating which can be optimised to fit the available time and resources.

2.2.7 Conclusions and key messages

The increasing availability of detailed and harmonised hazard datasets is calling for parallel efforts in the production of standardised multihazard exposure information for disaster risk models. GEDs can be a possible solution for harmonisation and for moving beyond single-hazard databases. Several recommendations can be distilled from this overview and are provided here to develop a roadmap towards the effective implementation of global, dynamic exposure databases. Finally, exposure data collection should be regarded as a continuous process sustaining a continuous re-evaluation of risks to enable an effective DRR.

Partnership

Authoritative and non-authoritative sources should be integrated in order to ensure quality standards and compliance with the disaster risk- reduction purposes. Within this context, it becomes important to harvest data from crowd-sourced information and exploit volunteered geographic information to augment authoritative sources and involve communities and experts, especially in data-poor countries.

Knowledge

The need for quality assessment and an analysis of the uncertainty in the exposure data to avoid error propagation. Quantification of exposure data uncertainty is useful for anatomising the structure of the total uncertainty in the risk assessment into individual uncertainties associated with the risk components (exposure uncertainty compared to that of hazard and vulnerability). In addition, the communication of uncertainty to the users of the exposure databases is also essential to ensure local understanding and trust in the data.

Innovation

Data and (statistical) models have to coexist in a statistically sound framework in order to overcome the impracticality of having a complete and fully enumerated global dynamic exposure database. Flexible integration of existing information at different scales and accuracies in order not to discard available information needs to be confronted. To this regard, rapid, large-scale data collection based on remote sensing should be fully exploited and be complemented whenever possible by information collected in situ using suitable sampling methodologies.

2.3 The most recent view of vulnerability

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Michael Hagenlocher

2.3.1 The importance of vulnerability for disaster risk assessment

2.3.1.1 Vulnerability: a key component to determine risks

Disaster risk is determined by the combination of physical hazards and the vulnerabilities of exposed elements. Vulnerability relates to the susceptibility of assets such as objects, systems (or part thereof) and populations exposed to disturbances, stressors or shocks as well as to the lack of capacity to cope with and to adapt to these adverse conditions. Vulnerability is dynamic, multifaceted and composed of various dimensions, all of which have to be considered within a holistic vulnerability assessment.

Vulnerability plays a fundamental role for understanding, assessing and reducing risks. When a hazardous event occurs — be it of natural, technological or man-made origin — the vulnerability of exposed people, objects (e.g. critical infrastructure, etc.) and systems (e.g. socioecological systems) at different scales is key to determine the severity of the impact. Though this fact has been widely accepted, the definition of vulnerability and the components it comprises varies between different authors and disciplines.

The United Nations Office for Disaster Risk Reduction (UNISDR Terminology, 2017) defines vulnerability as 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. This definition reflects the last decades' shift in the understanding of vulnerability from a focused concept (for example limited to physical resistance of engineering structures) to a more holistic and systemic approach. At the same time, it does not provide reference to the political/institutional situation and does not account for power relations or the heterogeneity within communities, which are aspects considered as important and included in the definitions proposed by other authors (Cardona et al., 2012; Alexander, 2013; Birkmann et al., 2013; Wisner, 2016)

Vulnerability represents a fundamental component of risk. A proper understanding of vulnerability comprising its dimensions as well as its root causes is important for effective risk assessment and risk reduction.

The significance of vulnerability for assessing risk is emphasised by the fact that the consequences of a hazardous event largely depend on human factors. That is, the hazardous event itself may be predominantly an external phenomena out of the control of those affected; any devastating impact caused by this event, however, is mainly influenced by inherent societal conditions and processes.

The L'Aquila earthquake in April 2009 in Italy is an example of a medium-power seismic event that had a disproportionately large human impact. It caused 308 fatalities, most of which were the young and elderly, as well as women. The death toll is partially linked to the high vulnerability of building stock in the mountains of Abruzzo. It is in part explained by the risk perception among female victims, who tend to be more fatalistic than men and who perceived their homes as a refuge, instead of leaving it (Alexander, 2010; Alexander and Magni, 2013).

The degree of vulnerability within a society or a population group is usually not homogenously distributed; social class, ethnic origin, age and gender may determine a lower or higher probability of being affected. Evidence of this fact has been shown by the impact of Hurricane Katrina, which caused a disproportionately high number of victims amongst the poor black and elderly population in New Orleans in 2005 (Cutter et al., 2006).

Addressing vulnerability — together with exposure — represents the gateway for risk reduction measures. Consequently, the importance of vulnerability for DRM is underlined by the Sendai framework for disaster risk reduction, claiming that understanding disaster risk (Priority 1) and developing related policies and practices need to consider the various dimensions of vulnerability (UNISDR, 2015a).

BOX 2.1

Resilience and capacities

Besides the notion of 'vulnerability' there are other terms and concepts addressing the possibility of harm to a system, people or specific objects by certain events and processes. Vulnerability – understood as a holistic and systemic concept – is closely related to and partly overlaps, for example, with the concepts of resilience and of coping and adaptive capacity.

'Resilience' is a term that has been widely used over the last years to describe characteristics related to the ability to absorb stresses, to respond to changes and to recover from shocks. Some authors see resilience as the positive flipside of vulnerability. A broader understanding of resilience incorporates the ability and willingness to learn, to reorganise and to undertake critical self-reflection (Alexander 2013; Kelman et al., 2016). Climate resilience has emerged into a new doctrine under the umbrella of which communities define the activities to combat the impending implications of climate change.

There are numerous related activities within Europe, for example the RESIN project is investigating climate resilience in European cities, the European Commission's FP7 project emBRACE has focused on community resilience and developed a set of key indicators for assessing it, and the Commission's Horizon 2020 project 'resilens' is scrutinising the resilience of European critical infrastructure.

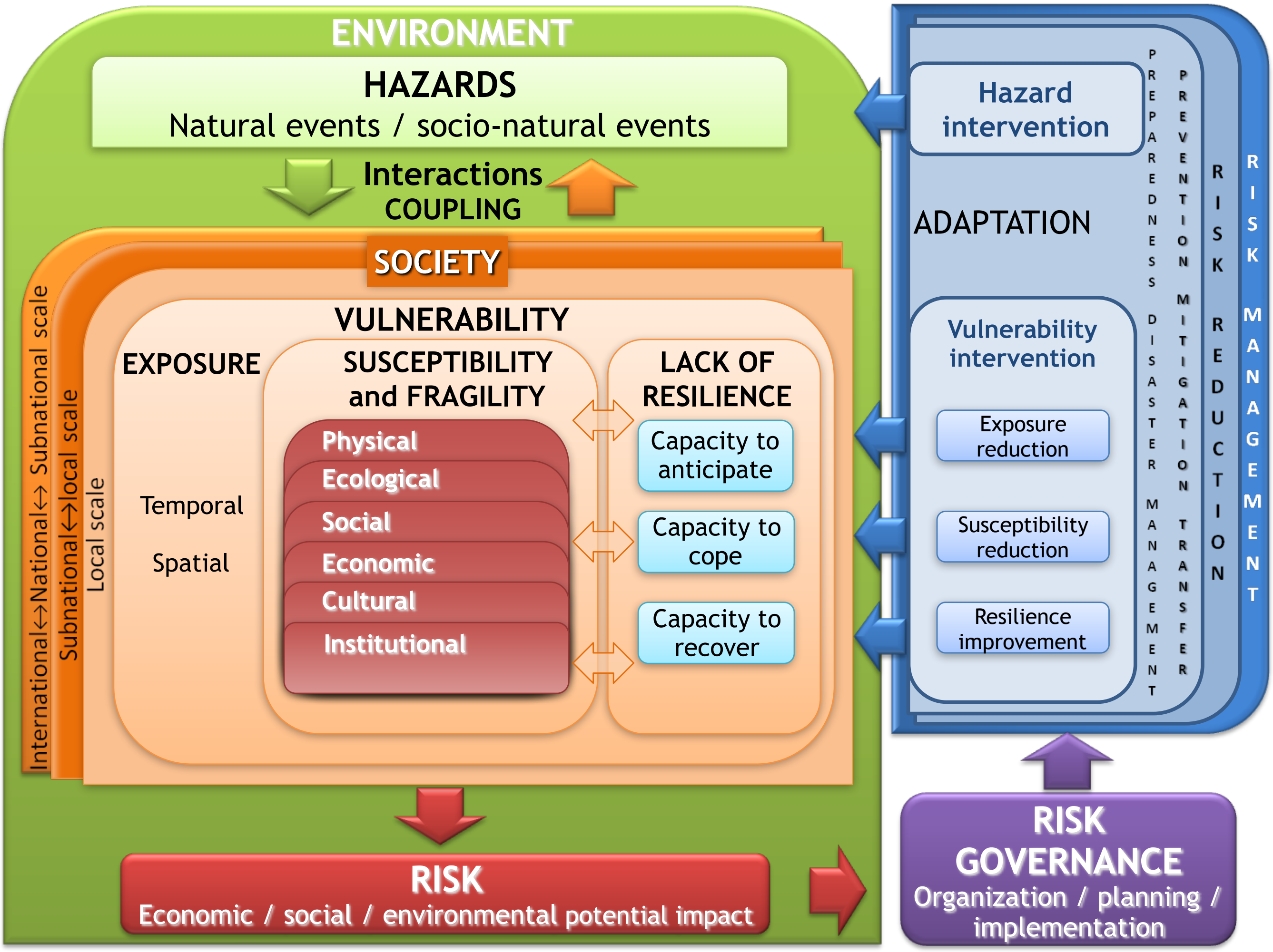
Just as the term 'resilience', the concept of capacities relates to the possibilities and abilities to reduce harm under hazardous conditions. Hereby, 'coping capacity' rather deals with the short-term conservation and protection of the current system and institutional settings, whilst 'adapting capacity' denotes a longer-term and constantly unfolding process of learning (Birkmann et al., 2013).

2.3.1.2 Conceptual issues and dimensions of vulnerability

Just as there are numerous definitions of the term 'vulnerability', there exist many models and concepts that describe vulnerability in its relation to other terms, such as resilience, exposure or capacities, and that elaborate on vulnerability's key dimensions. The European project 'Methods for the improvement of vulnerability assessment in Europe' (MOVE) developed such a concept, which attempts to represent the multifaceted nature of vulnerability (Figure 2.10). In its central part, it identifies six thematic dimensions of vulnerability: the physical, the ecological, the social, the economic, the cultural and the institutional dimension. All of these dimensions have to be considered within a holistic vulnerability study. The majority of assets and systems exposed to hazard will exhibit more than one dimension of vulnerability and hence these dimensions need to be addressed more in detail for any

FIGURE 2.10

The MOVE framework to conceptualise vulnerability
Source: Birkmann et al. (2013)



assessment (Birkmann et al., 2013). This framework is particularly useful within the context of disaster risk since it embeds vulnerability in the wider framework of risk governance/ management and emphasises the various intervention opportunities that may be taken to reduce risk.

A key initial question when scrutinising vulnerability is who or what is vulnerable to what type of threat or hazard. This leads to the question of how the interactions between hazards and vulnerabilities look like. In fact, there are significant differences in the way the various factors that determine vulnerability are linked or connected to different types of hazards. Typically, physical characteristics of elements at risk are directly linked to a particular hazard. For example, the degree to which a building withstands an earthquake is directly linked to the type of building material used. However, a great level of resistance related to earthquakes as a result of building material does not automatically imply that the ability to resist a flood event is similarly high. On the other hand, the predisposition to be adversely affected due to the economic, sociocultural or political-institutional susceptibilities is to a large degree hazard independent. A community, for instance, with a well-working emergency response system and a strong social network is better forearmed against any type of hazardous event than a community with corrupt public authorities and disrupted internal linkages (Brooks, 2003; Schneiderbauer and Ehrlich, 2006; Cardona et al., 2012).

Transferring these rather theoretical concepts into operational vulnerability assessments in practice results in a number of challenges. Most importantly, the majority of non-physical aspects of vulnerability are not measurable in the way in that we are able to determine temperature or people's income. Consequently, alternative methods for assessing vulnerability are applied. They can be quantitative or qualitative or a mix of both (see Chapter 2.3.4). Widely applied and accepted tools comprise vulnerability curves predominantly used for assessing physical vulnerabilities and the use of (proxy-) indicators, particularly to estimate the vulnerability of non-physical dimensions (for example social, economic or institutional vulnerabilities). Here, indicators are used to communicate simplified information about specific circumstances that are not directly measurable or can only be measured with great difficulty (Meyer, 2011). At local level, where spatial data and statistics often do not exist in sufficient resolution, expert opinions as well as participatory, community- based approaches play a major role in vulnerability assessments.

Power relations, cultural beliefs, the attitude towards risk- reduction efforts or the willingness and capacity to learn from previous events are essential for the degree of preparedness of a population. Related information can be found in story lines rather than in statistics. Another challenge lies in providing evidence about the degree of vulnerability and its causes. Vulnerability bears witness only in the aftermath of an event when damage and loss are realised. Loss and damage data, though strongly depending on the magnitude of the hazard itself, are therefore important data sources for vulnerability assessments and/or for the validation of assessment attempts (see Chapter 2.4).

Due to the conceptual complexity and methodological challenges connected with vulnerability, the uncertainties of vulnerability assessments and their results is a topic of ongoing discussion. The uncertainties are an aggregation of uncertainties from several sources. They include limitations in knowledge about the socioecological systems that the vulnerable elements are part of as well as inaccuracies of empirical data and limitations of models applied for vulnerability assessments.

Uncertainty can be classified in many different ways. One possibility is to subdivide it into 'aleatory uncertainty', which represents the variability of the properties of concern, and 'epistemic uncertainty', which stems from limited knowledge. A sophisticated estimation of uncertainties is usually a difficult and costly exercise. Hence, the level of complexity and sophistication and the effort and resources to be spent should be in line with the risk management issue and correspond to the level of detail needed.

2.3.1.3 State of the art and research gaps

The number of existing theoretical frameworks and concepts related to various aspects of vulnerability is striking. Future work should focus on the translation of these concepts into action, namely by developing easy-to-use tools to implement vulnerability studies that yield useful results for the stakeholder and user. At least within Europe, a set of standardised methods for defined purposes at certain scales would help to monitor changes over time and to compare vulnerability patterns spatially. The respective activities need to consider the developments of other relevant fields of action such as climate change adaptation or sustainable development.

The awareness of the significance of vulnerability for DRM has significantly increased over the last decades. Nevertheless, the importance of underlying triggering factors of vulnerability and not directly tangible aspects such as the cultural and institutional dimension requires further attention.

2.3.2 System and systemic vulnerability

In order to advance the understanding of vulnerability and its dynamics as well as to set appropriate policy agendas, it is crucial to look at how the vulnerability dimensions interact at different spatial, temporal and functional scales (Cardona et al., 2012).

The fact that our modern world is increasingly interconnected calls for systemic approaches when assessing vulnerabilities and risks, which take into account feedback loops and cascading chains of impacts

In particular, analysing vulnerability in the framework of sustainable development or climate change adaptation requires considering the interactions between human and natural systems.

2.3.2.1 System dynamics affecting vulnerability

Vulnerability is a dynamic concept (Cardona et al., 2012) and thus varies in space and time. Trends in exposure and vulnerability are influenced by changes in the demographic, economic, social, institutional, governance, cultural and environmental patterns of a system (Oppenheimer et al., 2014). Taking demography as an example, the current trend of an ageing population that characterises developed countries has considerably influenced people's vulnerability to heat stress, as shown by the high death toll paid by the elderly during the 2003 heatwave event in Europe (Robine et al., 2008).

Another example is the concentration of assets and settlements (and economic activities) in hazard-prone areas due to population growth and the lack of related spatial planning. At a first view this phenomena simply represents increased exposure values. At a closer look, it is strongly linked to vulnerability. Hazard-prone areas are in general characterised by lower land values and are thus occupied by low-income households. The scarcity or non-existence of infrastructure, services, social protection and security in these sites eventually leads to 'socially segregated' urban development, which in turn generates new patterns of vulnerability and risk (UNISDR, 2015b).

For instance, the most damaged areas during the 2010 floods in Bursa (Turkey) were those neighbourhoods characterised by the presence of informal settlements and occupied by low-income families (Tas et al., 2013).

Another aspect of systemic vulnerability is the dependence of human societies on ecosystem services, particularly those regulating climate, diseases and providing buffer zones (Millennium Ecosystem Assessment, 2005). For example, coastal wetlands increase energy dissipation of storm surges, dampen wind-driven surface waves, modify wind fields and reduce the exposure of (and thus protect) people and physical assets in the hinterland. Moreover, provisioning services include food, raw materials, fresh water and medicinal resources, the availability of which determines well-being and thus can strongly influence the socioeconomic vulnerability profile of a community. Consequently, ecosystem-based adaptation approaches have been applied in DRM to address potentially hazardous processes such as flash floods, heat waves, sea level rise, increasing water scarcity, etc.

2.3.2.2 System criticality

Globalisation has made communities and nations interdependent in a number of realms, including politics, economy, culture and technology.
A systemic view postulates to consider those linkages within and without a socioecological system that may affect its vulnerability, thus drawing attention to wider human and environmental processes and phenomena (Turner et al., 2003). In concrete terms, this means that systems and their popula-

tions are not only affected by hazards to which they are physically exposed but also — by means of cascading effects — to those experienced elsewhere. Recent disasters such as the eruption of Eyjafjallajökull in Iceland (2010), the floods in Thailand (2011), the Great East Japan Earthquake (2011) and Hurricane Sandy in the United States (2013) called attention to the severe effects of such cascades of disasters.

Cascading disasters can be exemplified by the vulnerability of critical infrastructure (Pescaroli & Alexander, 2016). When in 2003 a tree fell on a Swiss power line, causing a fault in the transmission system, 56 million people in Italy suffered the effects of the worse blackout in the country's history. 30 000 people were trapped on trains and many commercial and residential users suffered disruption in their power supplies for up to 48 hours (Johnson, 2007). At a larger scale, failures in the global supply chain highlight how the vulnerability of one system may depend on the resilience of another system working in far spatial distance.

The Swedish company Ericsson experienced substantial loss due to the vulnerability of a subsupplier. A 10-minute fire at Philips' plant in New Mexico, caused by a lighting hitting the electric line, translated into a loss in phone sales of about EUR 375 million (Jansson, 2004).

This was mainly because Ericsson took no action after Philips' reassurance about production returning on track in a week — which was not the case. On the contrary, Nokia, another big Philips customer, promptly switched supplier and it even re-engineered some of its phones to accept both American and Japanese chips. By doing so, it raised its profits by 42 % that year and managed to acquire new market shares (Economist Intelligence Unit, 2009). The Ericsson–Nokia example underscores the fundamental role played by coping capacity in reducing the adverse effects of experienced hazards. Moreover, it calls for drawing attention not only to the triggering event when considering cascading disasters, but more importantly to how vulnerabilities of different system's components may align and thus amplify impacts (Pescaroli & Alexander, 2016).

2.3.2.3 State of the art and research gaps

Disaster risk research often remains fragmented in a number of disciplines and focused on single hazards (Cutter et al., 2015), with limited interaction with other relevant communities. Research adopting a coupled human-environmental system approach in framing vulnerability has contributed to the integration of separate domains (Cardona et al., 2012).

Namely, the approach of ecosystem-based adaptation has transferred this holistic view into practice. Yet, the level of trans- and interdisciplinarity that would be required to implement truly systemic approaches in vulnerability assessment is rarely achieved. Hence, future applied research should follow an approach of coproduction of knowledge and need to integrate relevant disciplines. Relevant university education and training programmes should prepare young scientists and practitioners accordingly.

2.3.3 Vulnerability within the context of changing climate conditions

Climate change is one of the most prominent examples of an external biophysical stressor putting coupled human-natural systems at risk and the vulnerabilities to changing climate conditions has been the focus of many assessment studies. Originally, the understanding of 'vulnerability' in the community of climate scientists differed from that of the disaster risk research by encompassing the hazard component itself. That is, the projected change of relevant climate parameters was seen as part of the system's vulnerability to climate change (IPCC, 2007).

Knowledge on climate change is growing fast, but standardised vulnerability assessment approaches are lacking. Vulnerability assessment must consider changing socioeconomic, political and organisational conditions that determine possible vulnerability pathways.

The Intergovernmental Panel on Climate Change (IPCC) special report, Managing the risks of extreme events and disasters to advance climate change adaptation (IPCC, 2012a), and later on its fifth assessment report (IPCC, 2013) have introduced the concept of 'climate risks' and have hence worked towards converging the concepts of both communities. The currently ongoing integration of climate change adaptation and disaster risk- reduction approaches leads to an increase of knowledge and has the potential to foster network building and to develop more efficient policies. A respective report is under preparation under the lead of the European Environment Agency (EEA).

The IPCC's fifth assessment report identifies several ways in which increasing warming and climate-related extremes can have an impact on a socioecological system and focuses in particular on those complex interactions between climate and such systems that increase vulnerability and risk synergistically (Oppenheimer et al., 2014). One of them is the negative effect of climate change on human health, which results from a number of direct and indirect pathways.

Direct biological consequences to human health can derive from heatwaves, extreme weather events and temperature-related concentrations of pollutants; yet most of the impacts will be indirectly triggered by warming-induced changes in environmental and social conditions (Mc Michael, 2013) and are hence in their extent determined by respective vulnerabilities. Moreover, climate change induced adverse impacts on crop yields' quantity and quality can exacerbate malnutrition (Met Office & WFP, 2014) and thus contribute to new or stronger vulnerabilities to a range of diseases.

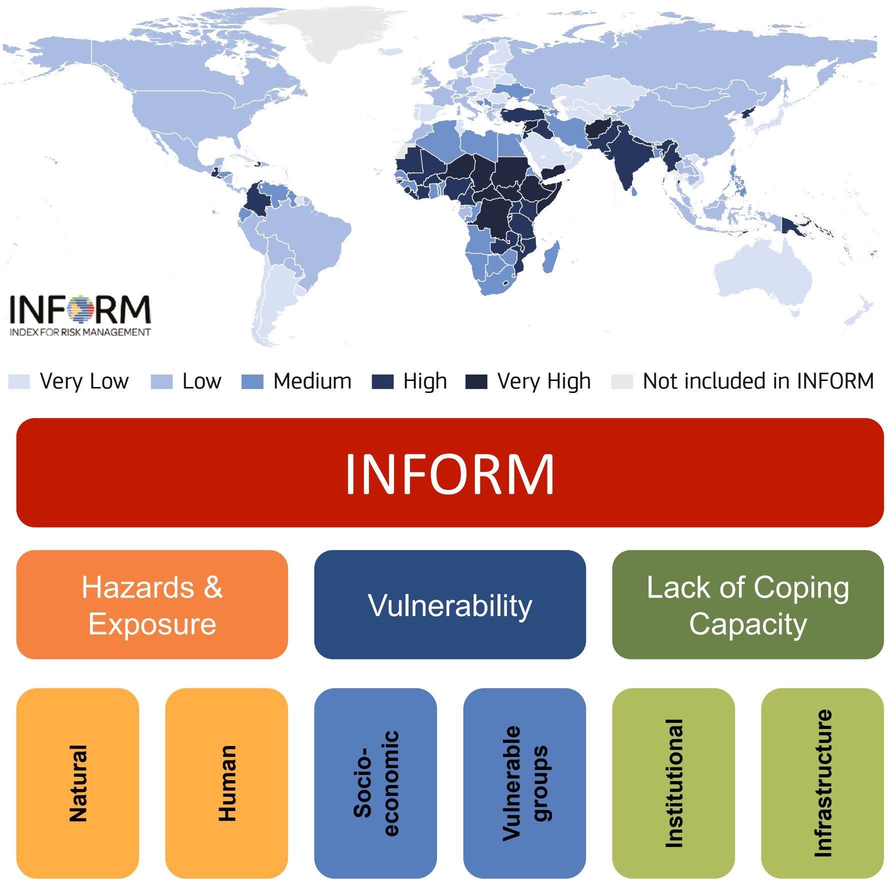
The assessment of climate-related risks and the identification of respective key vulnerabilities needs to consider the variety of these possible direct and indirect impacts. Useful tools to tackle this challenge are so-called impact chains, which represent cascading cause-effect relationships and allow for structuring assessment processes and the prioritisation of fields of action (Schneiderbauer et al., 2013; Fritzsche et al., 2014). Impact chains have, for example, been developed and applied by the ci:grasp adaptation support platform (n.d.) and the latest German climate change vulnerability study (Buth et al., 2015).

2.3.3.1 Vulnerability and climate change in Europe

At European level, climate change is recognised as an important driver of risk due to both climate extremes (for example heavy precipitation events or storms) and slow onset events of long-term duration (for example sea

FIGURE 2.11

Global maps of vulnerability index calculated by INFORM (upper left) approaches and the identified sub-components of risk and vulnerability left and the WorldRiskIndex on the bottom right.
Source: BEH and UNU-EHS (2016), INFORM (n.d.)

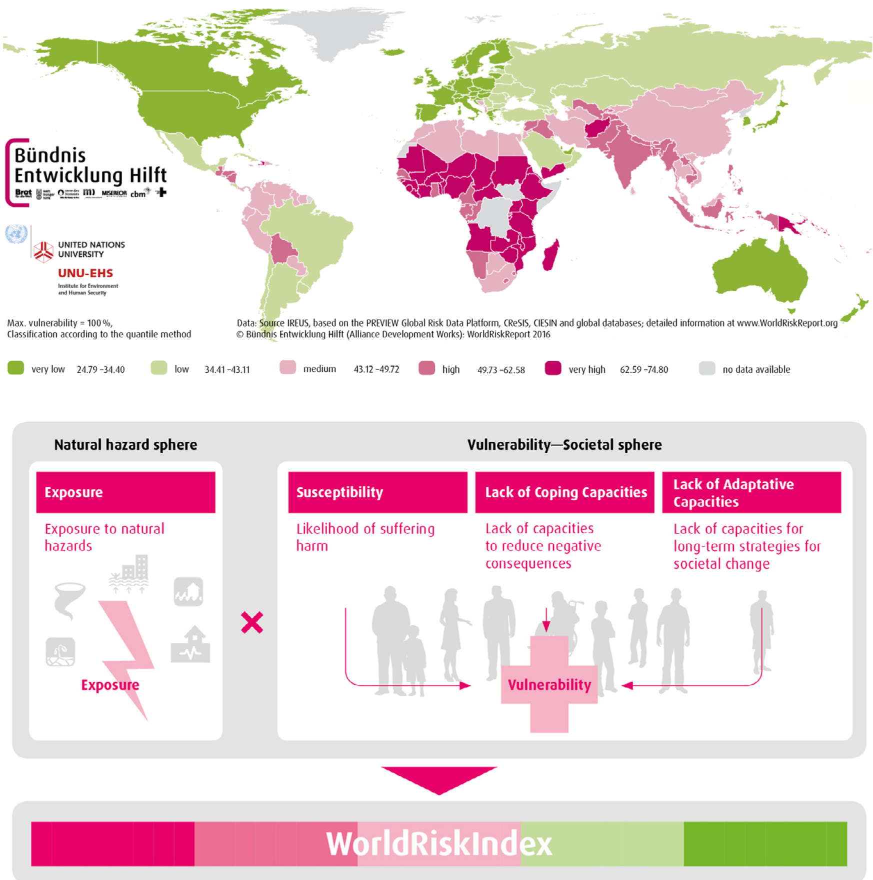


level rise or glacier retreat) Climate change will also have positive impacts in Europe in specific sectors and in certain regions (for example agriculture and tourism in northern Europe). In this chapter we concentrate on potential adverse impacts that require actions to reduce related risks.. Though all the countries in the EU are exposed to climate change, the related impacts vary depending on differences in climate conditions but also in vulnerabilities and degree of exposure (EC, 2013). Many EU Member States have based their national adaptation strategies on studies about risks and vulnerabilities to climate change, for example the United Kingdom in 2016 (UK, 2016), Germany in 2015 (Buth et al., 2015) and the Netherlands (PBL, 2012). At European level, respective studies have been implemented by the European Observation Network, Territorial Development and Cohesion (ESPON) in 2011 (EPSON, 2011) and the EEA in 2012 (EEA, 2012) and 2016 (EEA, 2017), as well as the European Commission in 2014 (Ciscar et al., 2014). The EEA hosts the European climate adaptation platform website that represents the knowledge hub for climate change risks and adaptation in Europe (Climate-ADAPT, n.d.).

Some key vulnerabilities related to climate change identified by these reports are:

- demographic change / aging population;
- population growth in low- lying urban agglomerations;
- vulnerability of (critical) infrastructure to warming and floods;
- increasing dependency on electricity, particularly linked with the increasing internationalisation of power grids.

and WorldRiskIndex (upper right). The respective underlying conceptual are shown in the lower part representing the INFORM index on the bottom



2.3.3.2 State of the art and research gap

The knowledge about future climate conditions is vast and continues to increase. There are numerous studies scrutinising climate change impacts and vulnerabilities. However, most of them have been carried out in a static context and they have not considered future socioeconomic developments resulting in changes of land use, urbanisation or demography. Besides climate scenarios, climate risk studies should aim to integrate vulnerability pathways.

Europe-wide climate risk assessment should further be supported and coordinated with the results from national and subnational studies, where appropriate. A certain level of standardisation is desirable in order to allow for comparison in space and time.

2.3.4 Approaches to assess vulnerability

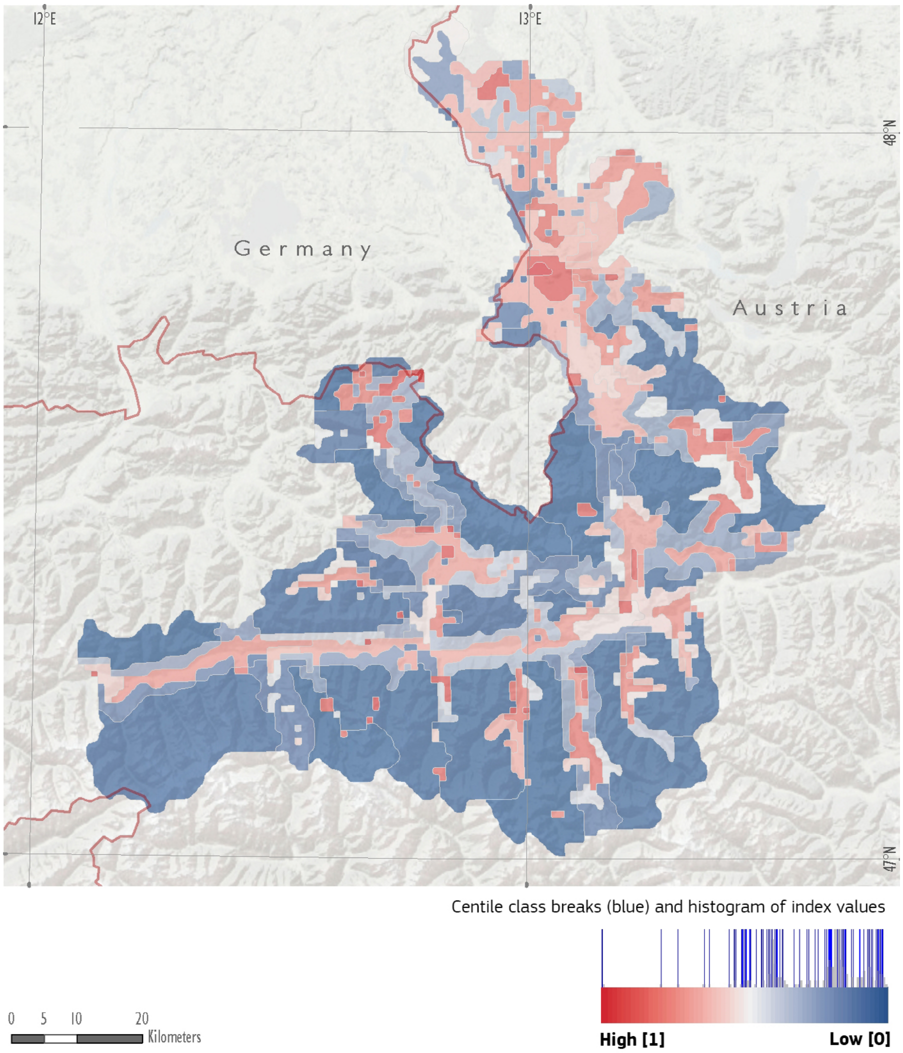
Researchers and practitioners apply quantitative, semi-quantitative, qualitative and increasingly mixed-methods approaches in order to assess vulnerability. Whether an approach is best suitable strongly depends on the objective and the scope of the assessment (e.g. understanding root causes, identification of hotspots, trend analysis or the selection of risk- reduction measures), as well as on the temporal and spatial scale; there is no 'one size fits all' approach.

Qualitative vulnerability analyses are based on experts' estimates. They are particularly useful if time and resources for the study are limited and if accessible data/information is not sufficient for quantitative analysis of complex phenomena. Qualitative assessment carried out with participatory techniques, such as interviews or focus group discussions, is particularly important for work at local/ community level and can reveal context-specific root causes for vulnerabilities. Quantitative assessments are often based on statistical analysis exploiting data about loss and damage related to certain hazards (see Chapter 2.3.4.1). The most widely employed alternative to this is the application of indicator-based approaches, which ideally allows assessing patterns and trends of vulnerability across space and time. The multifaceted nature of vulnerability cannot be adequately represented by a single variable (e.g. income per capita). Consequently, the generation of composite indicators has gained importance for grasping such complexities. It allows for combining various indicators into a vulnerability index and helps to translate complex issues into policy-relevant information.

At global level, there are a number of composite indicators to assess disaster risk, which represent vulnerability as one of the risk's dimensions next to hazard and exposure, for example the WorldRiskIndex (Welle and Birkmann, 2015; BEH and UNU-EHS, 2016) and the INFORM Index (De Groeve at al., 2014; INFORM, n.d.). Both are continuously updated multi-hazard risk indices aiming to support disaster risk reduction. The WorldRiskIndex is a means for understanding natural hazard related

FIGURE 2.12

Social vulnerability to floods in the Salzach river catchment, Austria. Source: Kienberger et al. (2014)



risks including the adverse effects of climate changes whilst INFORM is a tool for understanding risks to humanitarian crises and disasters. Conceptually, both indices are very similar. Their methodologies are presented in Figure 2.11. In the WorldRiskIndex, the vulnerability part comprises the components of susceptibility, coping capacity and adaptive capacity, which are represented by 23 indicators. In INFORM, vulnerability and lack of coping capacity are divided into two separate dimensions, which are described by 31 indicators. Figure 2.11 shows the countries' vulnerability scores based on data from 2016 calculated using the INFORM approach (left) and the WorldRiskIndex approach (right). Below these maps, the respective approaches and sub-components are visualised. Both indices started with an approach at nation-state resolution and global scale but strive for more sub-national applications of their methodology (Wannewitz et al., 2016).

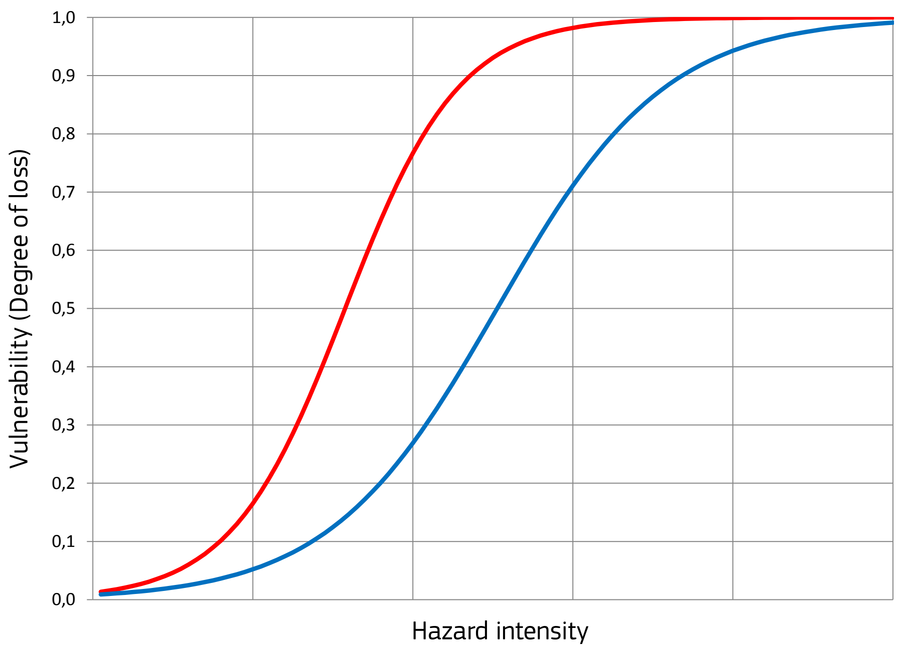
In Europe, a range of assessments have used spatial approaches, such as spatial multicriteria analysis or composite indicators to create maps at subnational level that facilitate the identification of hotspots and offer information for place-based intervention planning. For instance, a number of studies have investigated vulnerability in the context of river floods at different spatial scales. Examples include assessments: (1) in Vila Nova de Gaia, a flood-prone municipality in northern Portugal (Fernandez et al., 2016); (2) along the rivers Rhine, Danube and Elbe in Germany (Fekete, 2009); or (3) in the Salzach catchment in Austria (Kienberger et al., 2014) (Figure 2.12). Using indicator-based approaches, the three case studies identify a set of social (e.g. age, education and gender), economic (e.g. income, employment and dependency), organisational and institutional (e.g. early warning systems (EWS), access to health services, proximity to first responders, etc.) indicators and aggregate them into a composite index of vulnerability.

Composite indicators have the advantage to represent complex phenomena in a single value. If necessary, the underlying indicators or subcomponents of the index can be visualised separately to support the understanding of which factors contribute most to a positive or negative situation in the aggregated result (Hagenlocher et al., 2013). On the other hand, composite indicators are always data driven and might conceal crucial aspects that are not or cannot be expressed in numbers and statistics.

In recent years, there is an increasing number of studies aiming to understand and analyse vulnerability in multihazard settings. For example, Welle et al. (2014) present an approach for the assessment of social vulnerability to heat waves and floods as well as institutional vulnerability to earthquakes in the city of Cologne, Germany. While different sets of vulnerability indicators are used and aggregated to assess vulnerability to heat waves (e.g. age, unemployment, place of origin, etc.) and floods (age and occupan-

FIGURE 2.13

Generic quantitative vulnerability functions showing vulnerability (i.e. degree of loss) as a function of hazard intensity. The red curve represents a more vulnerable element and the blue curve a less vulnerable element. Source: courtesy of authors



cy rates per household), institutional vulnerability was evaluated using qualitative information obtained from a series of stakeholder consultations. Acknowledging the fact that communities are often affected by multiple hazards — combined, sequentially or as a cascading effect —, these studies present an important step towards providing solutions for real-world challenges.

2.3.4.1 Quantitative vulnerability functions

Potential damage to physical assets and loss of human lives are often assessed using quantitative vulnerability functions. These functions take into account the intensity of the hazard and the properties of the exposed elements. The intensity expresses the damaging potential of the hazard. Properties represent the resistance of the exposed elements such as building material and maintenance level. Vulnerability functions are widely applied to illustrate the relationship between hazard characteristics and fatalities and damage. Generic vulnerability functions are shown in Figure 2.13 and refer to physical vulnerability, described as 'the degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)' (UNDRO, 1984).

Vulnerability functions may be subdivided into fatality/mortality functions and damage functions (the latter denoted and formulated in different ways, e.g. loss functions, susceptibility functions and fragility functions). Damage functions are mainly based on empirical data collected in the aftermath of an event. Damage functions, in particular functions relating building damage to water depth, have a long tradition in the context of flood damage evaluation (Meyer et al., 2013). Physical vulnerability of buildings can also be assessed by physical models or by use of expert judgement. For some hazard types, fatality or mortality functions are developed to determine the death ratio for a single hazard parameter, e.g. water depth or earthquake magnitude. This allows the estimation of numbers of fatalities occurring at, for example, a certain water level. However, the development of fatality functions goes along with a high degree of uncertainty, which stems from the variety of physical and human parameters influencing the loss of life. For example, water depth may not be the only and most relevant intensity measure. Aspects such as flow rate, flood duration or sediment transport might be equally as important.

The most appropriate methodology to assess vulnerability strongly depends on the purpose and the context, as well as the temporal and spatial scales; there is no 'one size fits all' approach.

For quantitative physical vulnerability assessment, one can apply existing vulnerability curves, which are appropriate for the specific hazard and the exposed elements (e.g. building types) in study. Vulnerability curves have been developed for several types of natural hazards, such as wind storms, landslides, floods, tsunamis and earthquakes. There are curves expressing loss within the built environment as well as loss of human lives. Most of the curves are developed from empirical data and accordingly fit well with previous events in the area where the data was collected. For other locations a calibration or validation of the model is necessary prior to use. Validation is also needed for physical or analytical vulnerability functions.

Application of vulnerability functions is useful in several phases of the risk management, such as risk assessment and risk treatment. Risk analysts, scientists, stakeholders and decision-makers could be users of vulnerability functions with the purpose to provide input to:

- decisions about the question of whether risks need to be treated or about issues such as the prioritisation of risk treatment options of different areas and of different hazard types;

- identification of appropriate and optimal risk- reduction measures;

- financial appraisals during and immediately after a disaster as well as budgeting and coordination of compensation (Merz et al., 2010).

Alternatives to vulnerability curves are fragility curves, which also express the uncertainty in the physical vulnerability. Fragility curves have been widely applied in probabilistic risk and vulnerability assessment, in particular for earthquake risk (Hazus n.d.), but recently also for landslide risk assessment. These functions describe the probability of exceeding different damage states for various intensities. In a recent study on seismic risks in the city of Barcelona, Spain, a physical vulnerability assessment approach was first carried out based on vulnerability functions for different building types (e.g. unreinforced masonry or reinforced concrete, steel and wood buildings). In a second step this was combined with a probabilistic analysis of the seismic hazard into a seismic risk assessment for buildings across the city (Carreño et al., 2014). The authors also considered conditions related to social fragility and lack of resilience that favour second order effects when a city is hit by an earthquake. Factors such as population density, population with poor health or social disparity were used as proxies for social fragility. In addition, the operating capacity in case of an emergency, the state of development or the access to health services were used as indicators of lack of resilience and combined in an overall urban seismic risk index (Carreño et al., 2007). The results show that the population in the central parts of Barcelona lives at a considerably higher risk than those living on the outskirts of the city.

2.3.4.2 State of the art and research gaps

Indicator-based assessment methods have proved to support the drafting and prioritisation of disaster risk- reduction measures and strategies as well as the allocation of resources. Several challenges exist with respect to the dependency on data availability and quality, the validation of the applied methodology and related uncertainty analysis (Hinkel, 2011).

Vulnerability curves are widely applied for physical vulnerability assessment. Future activities should focus on the development of a repository of vulnerability curves with user guidelines for different hazard types and different types of assets. Research should work on the development and use of multiparameter vulnerability functions that are transferable, i.e. valid for different building types, and applicable for vulnerability changing over time and for multirisk scenarios.

In order to fill these gaps, more data are required for improving and calibrating existing models as well as for proposing new empirical vulnerability models (see Chapter 2.4). Data collection and analysis should be extended and streamlined through the use of remotely sensed data and geographic information system technology. The potential of Copernicus services and particularly of Sentinel data has not been fully exploited by the disaster risk community.

An additional challenge lies in the forward-looking nature of vulnerability. That is, vulnerability assessment needs to take into account those factors and processes that may not yet have become evident in past disaster situations. This is particularly valid in highly dynamic environments where both socio-natural hazards and vulnerability patterns might undergo rapid changes in the near- and mid-term future (Garschagen, 2014).

The importance to integrate uncertainty in vulnerability assessment has often been underlined but remains an issue of concern still today.

2.3.5 How vulnerability information is used in practice

The IPCC acknowledges DRM as a process that goes beyond DRR (IPCC, 2012b). Decisions to reduce disaster risk must be based on a sound understanding of the related vulnerabilities.

A requirement that has clearly been articulated in the SFDRR (UNISDR, 2015b) as one of four main priorities for action in the years to come.

2.3.5.1 Vulnerability in disaster risk management: from knowledge to action

Complementing hazard analysis, vulnerability studies generate information of relevance for various aspects of risk reduction and adaptation strategies, emergency management and sustainable territorial planning. They are of importance for all phases of the DRM cycle covering short-term response as well as long-term preparedness or recovery. Correspondingly large is the field of potential users of vulnerability information, including public administration staff who are responsible for civil protection or spatial planning, actors in the field of insurance, private companies running critical infrastructure, the civil society and, finally, any individual. One way of grouping the various purposes of vulnerability studies and their main users is to classify them according to

TABLE 2.1

Overview of vulnerability assessments, their main objectives and potential users at different spatial scales. Source: courtesy of authors

Scale	Main objective	Examples	Potential users
Global	Identification of spatial hot spots; allocation of resources; awareness raising	The vulnerability components of the following risk indices: INFORM index (De Groeve et al., 2015); World Risk Index (BEH & UNU-EHS, 2016); Disaster Risk Index (Peduzzi et al., 2009); Natural Disaster Hotspots index (Dilley et al., 2005)	International organisations (including donors); international non-governmental organisations (NGO); regional intergovernmental organisations
		Notre Dame Global Adaptation Index (ND-GAIN, n.d.)	
International/ regional	Identification of spatial hot spots; allocation of resources; awareness raising	The vulnerability component of the INFORM Subnational risk index for the Sahel and the Greater Horn of Africa (INFORM subnational models, n.d.)	International organisations (including donors); international NGOs; ROI
		Vulnerability to climate change in Europe (ESPON, 2011); climate change vulnerability mapping for Southeast Asia (Yusuf & Francisco, 2009)	
National / subnational	Identification of hot spots; development of risk reduction / adaptation strategies; allocation of resources; awareness raising; advocacy	The vulnerability component of the INFORM Subnational risk index (INFORM subnational models, n.d.) for Lebanon and Colombia, World Risk Index subnational for the Philippines (Wannewitz et al., 2016); Social Vulnerability Index for the USA (Cutter et al., 2003)	International organisations (incl. donors); international /national / local NGOs; national, subnational and local governments and public administration
		Numerous studies in Europe. For an overview of work related to climate change, see Prutsch et al., 2014	
Local	Identification of root causes; strengthening capacities of local actors; empowering communities	For an overview of vulnerability assessments in Europe with respect to natural hazards, see Birkmann et al., 2014;	International organisations (incl. donors); international / national/ local NGOs; national, subnational and local governments and public administration-affected communities
		A semi-quantitative assessment of regional climate change vulnerability by Kropp. et al., 2006	

spatial scale. Extending the examples presented above, Table 2.1 provides an illustrative overview of selected vulnerability assessments, their main purposes and potential users at different spatial scales.

Vulnerability assessment is used to support stakeholders and policymakers in prioritising various risks, in identifying root causes and spatial hotspots and in developing risk reduction strategies and measures.

The complexity of vulnerability and the wide range of possible applications of assessment studies require considerable effort to define the studies' scope (objective, target groups, spatial and temporal scale, spatial resolution of results, etc.). In practice, vulnerability studies have benefited from pursuing a process of co-production of knowledge. The integration of scientists, practitioners and potential users in the process of a vulnerability assessment right from the beginning usually results in a higher level of acceptance of their results. They are also more likely to be used in decision- and policymaking. An example is the latest vulnerability assessment for Germany within the scope of which a network of national authorities was created and which participated in all important decisions (Greiving et al., 2015).

2.3.5.2 Conclusions and key messages

Over the past decades, vulnerability research has made considerable progress in understanding some of the root causes and dynamic pressures that influence the progression of vulnerability and raised awareness that disasters are not natural but predominantly a product of social, economic and political conditions (Wisner et al., 2004).

Vulnerability assessments are a response to the call for evidence by decision-makers for use in pre-disaster risk assessment, prevention and reduction, as well as the development and implementation of appropriate preparedness and effective disaster response strategies by providing information on people, communities or regions at risk.

The following steps are proposed to further improve vulnerability research and related applications with the final aim to inform policymakers to most appropriately:

- co-produce knowledge in a transdisciplinary environment;
- evaluate and present inherent uncertainties;
- integrate intangible but crucial factors into quantitative assessments;
- develop and apply methods that allow for considering cascading and multirisks;
- combine vulnerability scenarios with (climate-) hazard scenarios when assessing future risks;
- empower communities to better understand and reduce their vulnerability in order to make them more resilient to identified hazards;
- design and facilitate multilevel and cross-sectoral feedback loops between public, practitioners and policymaking bodies (local, regional, national and European) and other stakeholders;
- standardise vulnerability assessment approaches in order to allow for more comparison (in space and time);
- work on improved evidence within vulnerability assessment — this requires continuous effort to improve loss and damage data.

Partnership

The comprehensive analysis and assessment of vulnerability requires an interdisciplinary approach involving both natural and social sciences. In addition, in order to foster sustainable and efficient vulnerability reduction strategies and measures, an approach to produce knowledge co-productively is desirable. This calls for a partnership with affected communities, practitioners and decision-makers. A stronger link and enhanced interaction with other relevant communities is desirable, namely climate change adaptation, natural resource management, public health, spatial planning and development.

Knowledge

The determination of risk often remains hazard centred and hazard specific and does not consider vulnerability appropriately. Vulnerability assessment has tended to be mostly quantitative in nature. Cultural aspects as well as formal (procedures, laws and regulations) and tacit informal (values, norms and traditions) institutions play a fundamental role as both enabling or limiting factors of resilience and have not gained sufficient attention. A challenge is the need to consider local data and information in order to account for small-scale specificities of vulnerability. Present databases on damage and loss caused by natural hazards should be standardised and extended to support evidence building in vulnerability assessment. Existing barriers in the co-production, exchange and use of knowledge have to be understood and minimised.

Innovation

In recent years, improved approaches to assess vulnerability by statistical analyses or indices have been established. Fostering the integration of Earth observation data and technology to detect changes would improve the possibility to represent some of the dynamic aspects of vulnerability. Further improvement requires enhanced event and damage databases and more sophisticated methods for potential future vulnerability pathways and their integration into risk scenarios. The challenge to integrate qualitative information, which often contains crucial facts, needs to be addressed. Observation data and technology to detect changes would improve the possibility to represent some of the dynamic aspects of vulnerability. Further improvements require enhanced event and damage databases and more sophisticated methods for potential future vulnerability pathways and their integration into risk scenarios. The challenge to integrate qualitative information, which often contains crucial facts, need to be addressed.

2.4 Recording disaster losses for improving risk modelling capacities

Scira Menoni*, Costanza Bonadonna, Mariano García-Fernández, Reimund Schwarze*

2.4.1 Relationship between pre-event risk modelling and post-disaster loss data

Pre-event risk assessment and post-event damage estimation are more linked than is generally thought. As shown in Figure 2.14, either probabilistic or deterministic damage forecasts are appraised in pre-event risk assessment, whilst in the aftermath of the event, the scenario that occurred is analysed. Both modelled and estimated damage can regard one or few exposed items or multiple sectors ranging from businesses to lifelines (available in fewer cases). Damage can be expressed as physical damage to items and/or monetary costs of repair or as loss to individual economic sectors or to a given economy and society as a whole.

In the case of the pre-event assessment, hazard, exposure and vulnerability are the components that need to be evaluated and combined in order to obtain a risk assessment. In the post-event analysis, the estimated damage must be described on the basis of the observed hazard features, on the configuration of exposed systems and on their vulnerability at the time of the event.

Pre- and post-damage assessment have more in common than generally perceived; in both cases there is a need to understand the relative contribution of hazard, exposure and vulnerability factors on the overall damage.

There is still a debate on the meaning of damage and losses and which types should be considered; here, an interpretation based on previous EU projects and available literature is proposed (Merz et al., 2010; Meyers et al., 2015; Van der Veen and Logtmeijer, 2005). As can be seen in Figure 2.15, damage due to natural hazards is generally divided into damage to tangible objects and assets, meaning those for which a monetary assessment is easily obtained and not controversial, and damage to intangibles, meaning values such as human life, historic heritage or natural assets for which monetisation is either extremely difficult or controversial. Damage to both tangibles and intangibles can be direct, meaning the damage provoked by the hazardous stressor, or indirect, which is consequent upon the direct damage (e.g. production loss due to damaged machinery) or upon ripple effects due to the interdependency of economic systems, both forward and backward linkages. Whilst direct damage generally occurs locally, indirect damage can develop over much greater time and space scales, also far from the event's 'epicentre' and long after the event has occurred. In some methodologies, damage and losses are distinct: the first term refers to affected infrastructure and buildings, whilst the second refers to economic losses (GFDRR, 2013). In the following sections, the link between pre- and post-event damage and loss assessment is discussed, showing the contribution that enhanced post-disaster analysis can make in terms of knowledge and information to improve the quality and comprehensiveness of pre-event risk models.

Examples will be taken from three distinct hazard domains, such as earthquakes, floods and volcanic eruptions, in order to provide evidence for more theoretical assumptions. These natural disasters were chosen because of their diversity, the difference in terms of types and the extent of damage they produce. However, their use is just paradigmatic. Experts in other fields will be able to find correspondences to the hazard risk they are more familiar with.

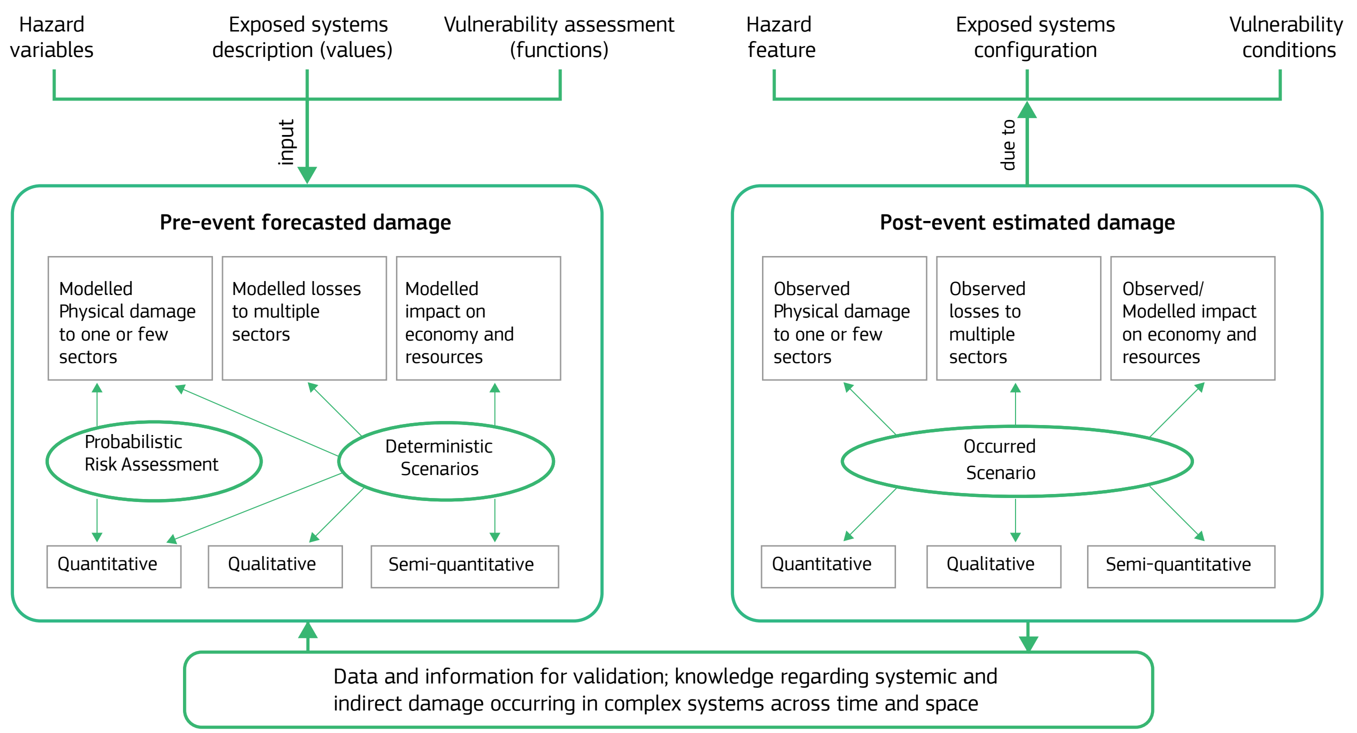
2.4.2 How post-disaster damage has been used to develop risk models: state of the art in a nutshell

2.4.2.1 State of the art of risk models

Expected damage can be assessed using quantitative, qualitative and semi-quantitative risk models (Figure 2.14, see also Chapter 2.1). Quantitative risk assessments dominate in

FIGURE 2.14

Pre - and post - disaster damage assessments
Source: courtesy of authors



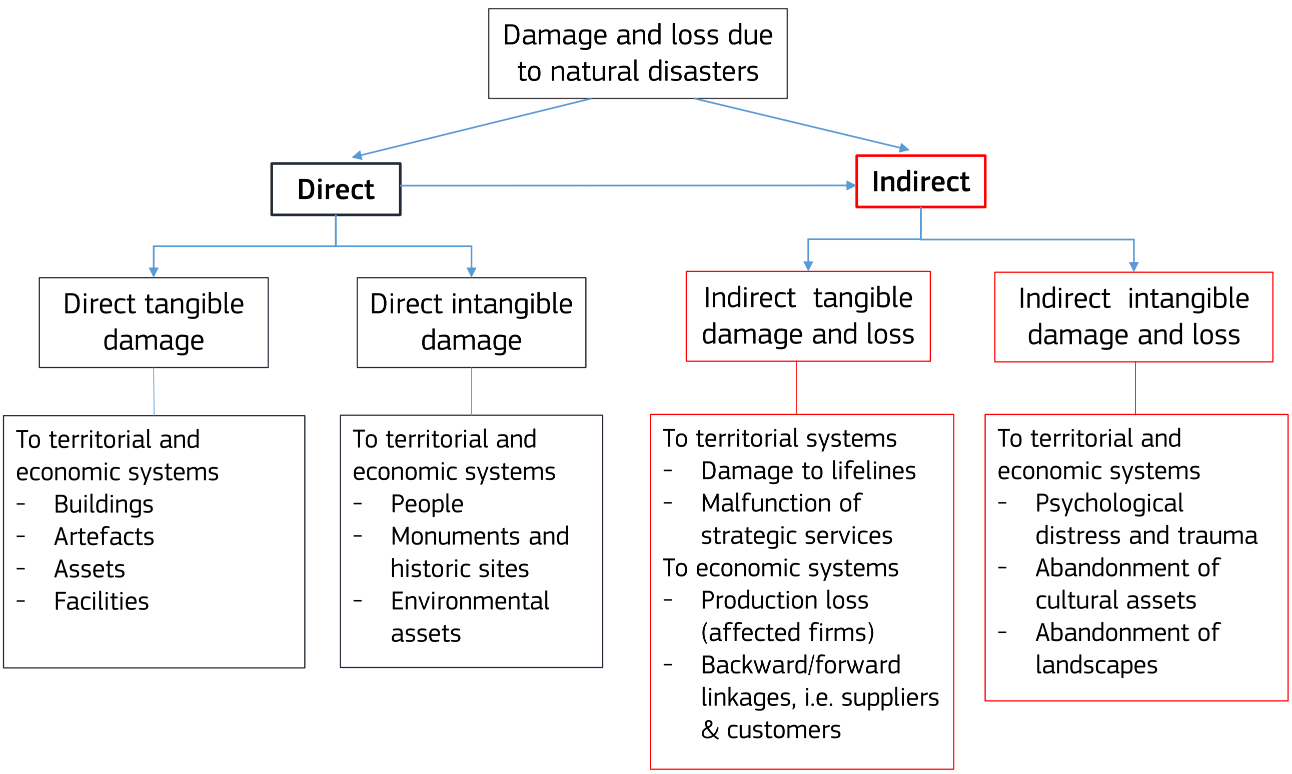
scientific journals; however, they generally consider quite a limited number and type of variables. More complex understandings of risk, which also comprise the consequences on the social, economic and environmental systems as well as on complex built systems such as critical infrastructures, are inevitably covered by a mixture of quantitative and qualitative appraisals (OECD, 2012; Theocharidou and Giannopoulos, 2015; Menoni et al., 2007). In the more widely accepted definition, risk is measured in terms of expected damage (probability of expected damage or deterministic damage scenarios) and is obtained as a function of hazard, exposure (see also Chapter 2.2) and vulnerability (see also Chapter 2.3). Whilst the first two aspects are provided in quantitative terms, the last one is often assessed through more qualitative or semi-qualitative approaches (Turner et al., 2003; Petrini, 1996). In the past, risk assessments were actually mainly hazard analyses, whereas in more recent times, quantitative appraisals of exposure have been increasingly included in risk assessment. Besides exposed people and assets, more realistic evaluations take into consideration their relative vulnerability as well, intended as the susceptibility to damage, which is an intrinsic measure of weakness and fragility (Mc Entire, 2005; Scawthorn, 2008).

Vulnerability and damage functions have been the most widely used tools, especially by engineers, to deal with pre-event damage assessment fed by post-disaster statistical data.

The capacity to assess the latter is more recent and restricted to some exposed elements and systems, with

FIGURE 2.15

Definition of direct and indirect damage
Source: Merz et al. (2010)



the obvious difficulty of constructing a comprehensive and coherent picture of what the total effect of a disaster in a given area may be (Barbat et al., 2010).

In the following section, the state of the art in vulnerability or damage functions in the field of seismic, volcanic and flood hazards are provided, highlighting similarities and differences. Vulnerability or damage functions are used to correlate hazard indicators (such as acceleration or water depth) with damage (such as damage index or monetary cost of repair and recovery).

2.4.2.1.1 How vulnerability/damage curves have been developed for seismic risk

Seismic engineers have started developing vulnerability curves long before colleagues in other natural hazards fields, coherent with the fact that the only possible protection measure against earthquakes is reducing buildings' vulnerability. Early seismic vulnerability methods were proposed in the seventies in Japan and the United States, and were being developed during the eighties in Europe (Corsanego, 1991; Senouci et al., 2013). Main European seismic vulnerability methods include GNDT (Benedetti et al. 1988), Risk-UE (Lagomarsino and Giovinazzi, 2006) and Vulneralp (Guéguen et al., 2007). Thus, the seismic field set the floor for a general methodology that was followed in other fields as well; it can also be considered as having general relevance. First, damage after earthquakes was observed in a very large number of cases and in structures differing in their layout, material, typology, age, resistant systems, etc. Two relevant results were achieved: on the one hand, a very large database with hundreds of failure cases was developed, and on the other hand, the specific factors determining buildings' response to earthquakes were identified. Such factors have been translated into parameters, as in the example provided in Table 2.2 (Zonno et al., 1998). In the practical application of the latter, the vulnerability of buildings is obtained from the weighed sum of the score assigned to each parameter, ranging from A (no vulnerability) to D (very high vulnerability), and multiplied by a weight expressing the relative relevance of the parameter.

TABLE 2.2

Indicators to assess seismic risk
Source: Zonno et al. (1998)

	PARAMETERS	VULNERABILITY CLASS				WEIGHT
		A	B	C	D	
1	Organization of resistant elements	0	5	20	45	1
2	Quality of resistant elements	0	5	25	45	0.25
3	Conventional Strenght	0	5	25	45	1.5
4	Building position and foundations	0	5	25	45	0.75
5	Floors	0	5	15	45	var
6	Plan Shape	0	5	20	45	0.5
7	Elevation Shape	0	5	20	45	var
8	Maximum distance between walls	0	5	20	45	0.25
9	Roof	0	15	20	45	var
10	Non structural elements	0	0	20	45	0.25
11	Maintenance conditions	0	5	20	45	1

Second, vulnerability curves are compiled by plotting seismic severity (on the horizontal x axis), expressed, for example, as acceleration, versus the percentage of damage or a damage index between 0 and 1 (on the vertical y axis). At maximal stress, any building is expected to collapse, whereas at no stress no building is expected to be damaged; anything in between, the intrinsic vulnerability of buildings is likely to produce differential damage. As a third step, a comparison between modelled damage based on vulnerability curves and post-event observed damage should be carried out as discussed in Chapter 2.3.

2.4.2.1.2 How vulnerability/damage curves have been developed for volcanic risk

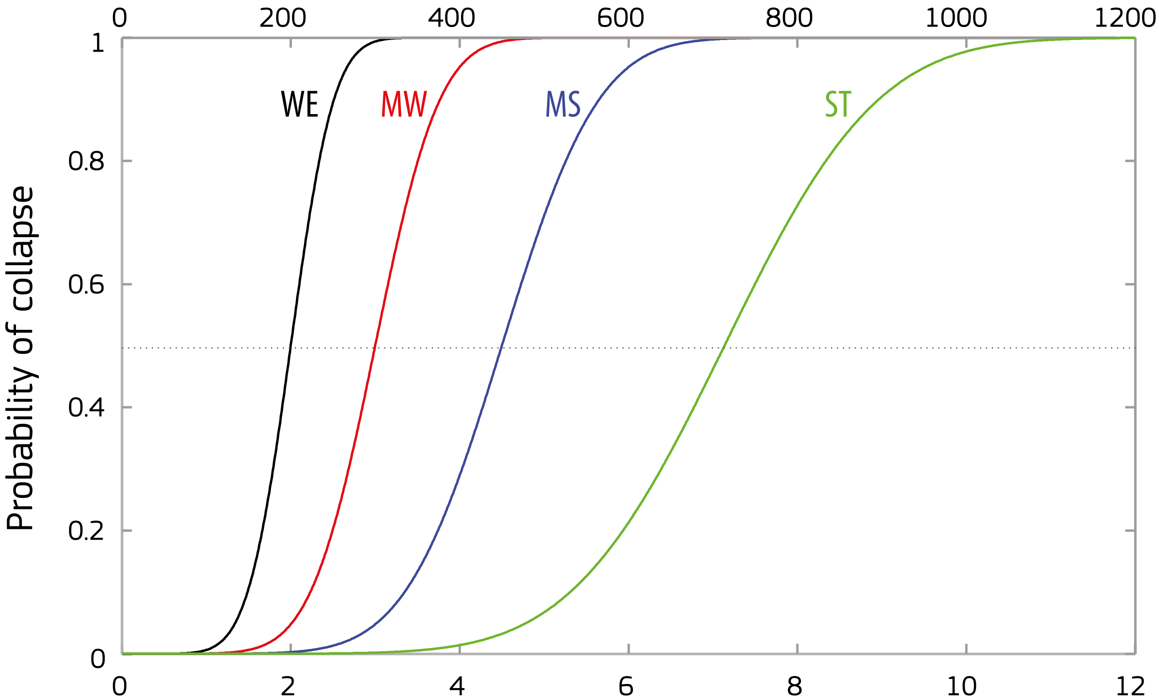
Vulnerability curves in volcanology have been developed much more recently and are available only for some of the hazards that may be triggered by an explosive eruption. More specifically, vulnerability curves describing the collapse of roofs are available for tephra fallout (e.g. Figure 2.16), while initial curves have been proposed for ballistic and pyroclastic flows in EU funded project MIAVITA (n.d.) (see also in Chapter 3.2 for the description and definition of volcanic hazards). The lack of vulnerability data for other hazards includes the unfeasibility of building constructions that are able to stand the stress due to lava or pyroclastic flows. Exposure, i.e. the location of constructions, becomes more important. In addition, given the relative low frequency of large volcanic eruptions affecting largely inhabited places, damage to modern structures could be observed only in a limited number of cases and mostly related to the collapse of roofs under tephra load. This is why vulnerability curves have been developed only for the damage to building roofs due to tephra fallout (Figure 2.16). The effect of tephra on other exposed elements, e.g. agriculture and infrastructures, have also recently been attempted (Wilson et al., 2014; Craig et al., 2016).

2.4.2.1.3 How vulnerability/damage curves have been developed for flood risk

It should be highlighted that in the flood case, scholars refer to damage rather than vulnerability curves, even though the followed method is very similar. Curves are plotted on a plane with an x axis that generally reports water depth and a y axis where damage is reported as costs of repair. Curves represent types of buildings differing for the number of floors, material, presence of basement or not and occupation of the first level. For a comprehensive overview of such curves, one may refer to the work of Jongman et al. (2012) and Thieken et al. (2008). Both recognise the limitations of current methods that neglect hazard severity variables such as velocity or sediment transport, which may be more relevant than water depth as a damage cause, especially in the case of flash floods.

FIGURE 2.16

Damage curves for collapse of roofs associated with tephra fallout
Source: Biass et al. (2016)



2.4.2.2 Key aspects of currently used vulnerability and damage curves

The brief discussion of the three domains permits to highlight some commonalities: first, the philosophy according to which vulnerability is represented by curves that depend on the intrinsic characteristics of different types of structures; second, the need of a statistically meaningful population of observed damaged buildings to develop vulnerability or damage curves; and third, vulnerability or damage curves are available for a limited set of structures and a limited number of sectors. They are largely available for residential buildings, far less for industrial facilities and even less for infrastructures. This restricts the capacity to construct comprehensive quantitative risk assessment for all assets and sectors. Furthermore, whilst vulnerability curves are derived from the observation of individual objects, risk assessment is developed for an area or a region. Therefore, risk assessment is based on the hypothesis that assets in a given region can be averaged in terms of their vulnerability features.

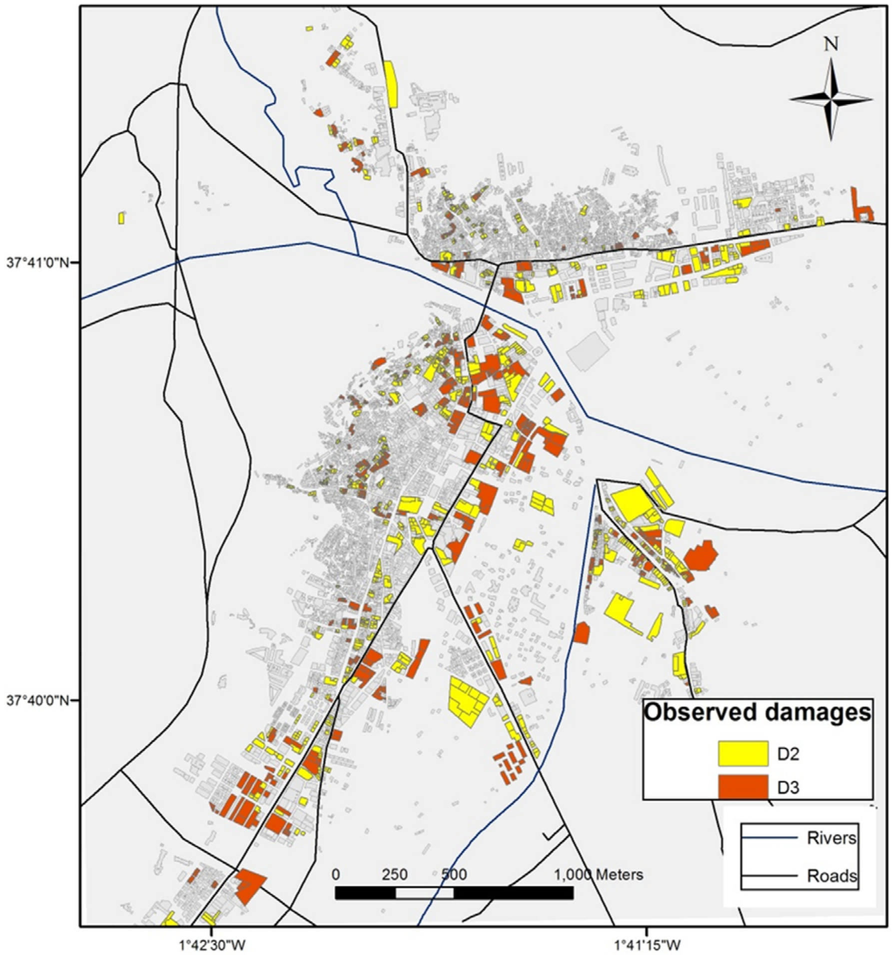
Another factor limiting the possibility to transfer such curves from one geographic area to another derives from the fact that the observed damage and relative vulnerability factors are highly context dependent, as they are linked to the types of buildings and structures that have been surveyed. This is the reason why consulting firms that provide insurance and reinsurance companies with immediate figures of loss due to a recent calamity carry out post-disaster surveys. The rapid evolution of information technology information technology has given an important impulse to the use of risk assessment scenarios by means of very large datasets comprising information on land uses and basic built stock characteristics that can be digested in a rather short time. However, feedback from real events is crucial to increasing the reliability of their modelling capacity (Marsh, 2015).

2.4.2.3 Use of post-event damage data for evaluating the reliability of risk models results

Even though separate events that have occurred cannot provide a com-

FIGURE 2.17

Observed building damage in the city of Lorca in terms of mean damage grade (D1: slight, D2: moderate, D3: heavy and D4: partial collapse) for the Mw5.2 earthquake on 11 May 2011
Source: DG Citizen Security and Emergencies of the Region of Murcia

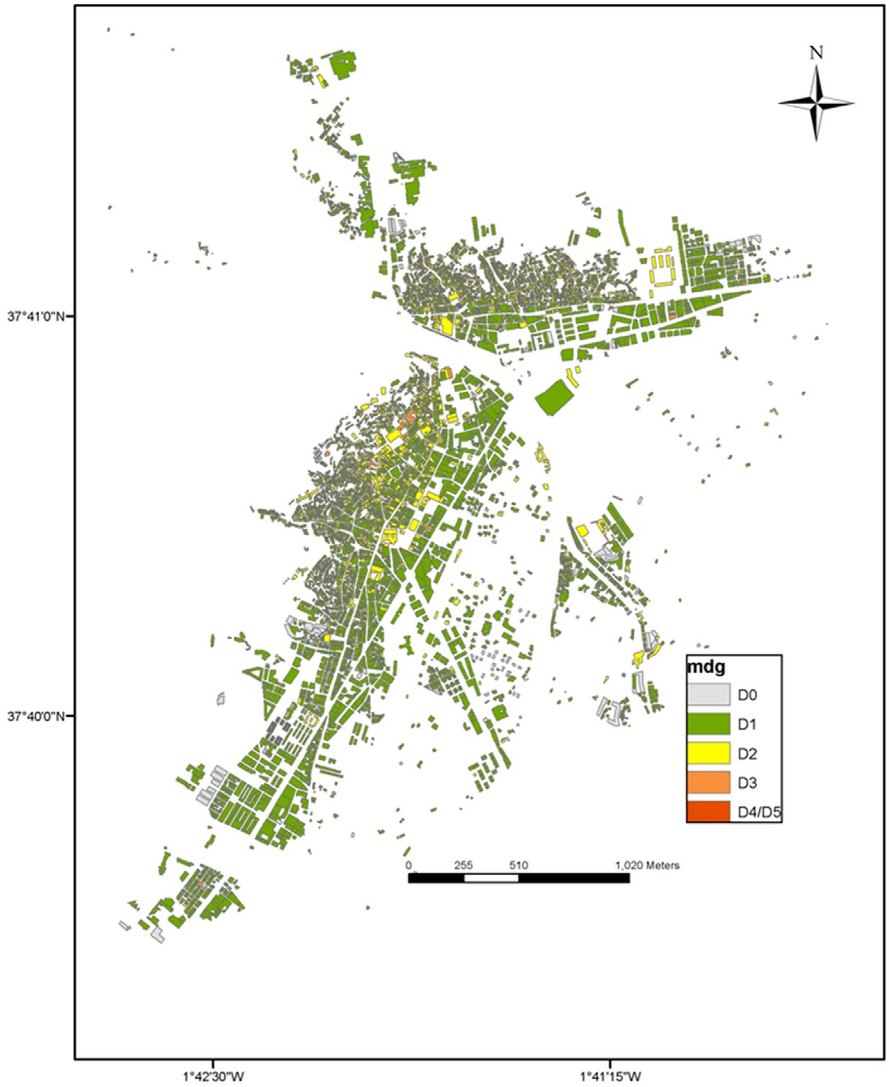


prehensive validation for risk models, they can be used to assess the discrepancies between the model forecasts and observations.

Here the comparison between pre- and post-damage assessments conducted for the city of Lorca in Spain is provided. Figure 4 shows the actual observed damage in the most affected suburbs in Lorca as a consequence of the earthquake that occurred on 11 May 2011. Figure 2.18 represents the modelled damage using Risk-EU approach (Lagomarsino and Giovinazzi, 2006), considering the seismic load by the observed European macroseismic scale (EMS-98) intensity and the vulnerability index by building typology, age and number of floors.

FIGURE 2.18

Simulation of physical damage to buildings in the city of Lorca using the direct approach.
Source: courtesy of authors



The comparison between Figure 2.17 and Figure 2.18 shows that the modelled scenario underestimates the damage, particularly for the highest damage levels. This suggests the need to consider additional vulnerability factors such as the state of preservation, orientation, discontinuities, soft story buildings, plan/vertical irregularities, openings and quality of construction that were missing in the pre-event vulnerability appraisals. Also, in this specific case, there could be possible previous effects from a M4.5 foreshock.

2.4.3 Damage and losses to multiple sectors: relevance for more comprehensive risk assessments

Exercises similar to the one briefly shown in Chapter 2.4.2.3 are very important to evaluate the consistency of risk models; however, they are often limited to a restricted number of assets and to direct physical damage. In the following, the state of the art in risk assessments and damage estimations by sectors will be shortly discussed, distinguishing between tangible and intangible exposed assets. Needs in terms of future damage data provision are also discussed.

2.4.3.1 Damage to tangibles

2.4.3.1.1 Agriculture

As suggested by Brémond et al. (2013), damage to agriculture should comprise different elements: crops, soil, infrastructures and storage facilities, which are differently exposed and vulnerable to various hazards such as earthquakes, volcanic eruptions and floods (FAO, 2015).

Post-event damage assessment can provide a more comprehensive understanding of damage to multiple sectors including agriculture, infrastructure, services and industrial and commercial activities, overcoming the narrow approach taken so far.

Earthquakes have usually been associated with potential damage to storage facilities for animals or machinery; not much thought has been given to infrastructures used in agriculture. Nonetheless, the 2012 earthquake in Italy proved to be devastating for hydraulic infrastructures needed for irrigation that was halted for several days with heavy consequences for production.

Damage due to volcanic hazard, in particular gas and tephra, is associated with animals, crops, irrigation water and soil that can be devastated for a long time (Craig et al., 2016).

Floods may affect all above mentioned components differently, but as mentioned by Brémond et al. (2013), this is not reflected in currently available damage curves.

2.4.3.1.2 Industries and commercial businesses

Industries and commercial businesses are often treated as buildings, even though they differ from the latter in many regards. A first difference is the large space usually necessary for activities that make these facilities more vulnerable to earthquakes. Secondly, potential damage to machinery and raw and finished products may be more relevant than damage to structures, particularly in the case of floods, where damage to structures is generally low.

Thirdly, businesses present a very large combination of buildings, machinery, activities and processes that make it hard to standardise vulnerability assessment. Information on damage suffered by industries and factors that make them vulnerable are available for flood risk and earthquakes (Suzuki, 2008; Krausman, 2010). Damage to business can sometimes turn into a severe secondary hazard (risk cascade), when dangerous plants are affected by natural hazards producing the so called Natech hazards (Cozzani et al., 2010; Ministère chargé de l'environnement, 2005; see also Chapter 3.14).

2.4.3.2 Damage to intangibles

Damage to intangibles is that which affects people and artefacts that are considered of incommensurable value, i.e. it is very difficult or controversial to monetise. Consideration in this paper will be limited to three examples, one for each hazard.

2.4.3.2.1 Loss of cultural heritage due to earthquakes

Earthquakes occurring in historic towns often affect ancient buildings and monuments more permanently and dramatically. Their vulnerability is due to several factors including construction material, type of resistant technology, lack of maintenance and poor or totally lacking seismic retrofitting. Furthermore, historic centres in Mediterranean areas, e.g. Greece, Spain, southern France, Italy and Slovenia, are characterised by complex urban blocks. The vulnerability of these blocks is exacerbated by the presence of shared structural components between adjacent buildings, topographic layout and the recent introduction of infrastructures, without taking seismic risk into sufficient consideration. From a cultural perspective, it is very difficult to assess the value of lost heritage. Methods are available but evaluations are always heavily loaded with societal and emotional concerns that are hard to represent in formalised quantitative terms.

2.4.3.2.2 Loss of natural assets and soil as a consequence of floods

Floods may damage, for example, parks and natural preserves in different ways (Gautak and Van der Hoek, 2003): light structures used for visiting such areas may be destroyed and contamination due to toxic and dangerous substances carried out by inundating waters may occur with different degrees of severity, while fauna and flora may also be affected. When a post-flood damage assessment was conducted it was observed that certain species of birds abandoned the area due to the loss of nutrients in the soil and water (Menoni et al., 2017). Time is required in order to assess whether or not such damage is permanent and whether or not eventual substituting species are as rich in biodiversity as those they have substituted. Similar considerations may regard the soil itself for agricultural purposes. Salinisation resulting from coastal inundations and loss of fertile soil may be more or less permanent. Those observations should lead to enhanced risk models that provide an output to show not only the immediate damage due to the event, but also its evolution and dynamic over time, which may require years to appraise the real, longer-term effects.

2.4.3.3 Historical examples of permanent relocation

Loss of social capital as a result of temporary or long-term relocation is an issue that should be considered whenever such a measure is examined. Sometimes during volcanic crises, such a decision is inevitable to safeguard people's life. Examples of past relocations such as those associated with the 1982 El Chichón eruption in Mexico (Marrero et al., 2013), the 1991 Pinatubo eruption in the Philippines (Newhall and Punongbayan, 1997), the 1991 Hudson volcano eruption in Chile (Wilson et al., 2012) and the 2010 Merapi eruption in Indonesia (Mei et al., 2013) suggest that without careful planning, communities can be largely disrupted. In all these examples, people were detached from their source of income and from the territory that is often a fundamental component of their livelihood and identity.

2.4.4 The relevance of indirect damage and losses to account for the complexity of events

Literature on direct, indirect and secondary damage is rather significant and there is still no perfect consensus on what those terms mean; however, larger convergence by the scientific and practitioner communities has been achieved in more recent years thanks to efforts at the European and international levels.

At the former level, one may consider the results of the Conhaz project (Meyer et al., 2015), the Nedies project (Van der Veen et al., 2003) and, lately, the work carried out by the European Commission on disaster loss data (De Groeve et al., 2013; EU technical working group, 2015). At the international level, the work carried out within ECLAC (Cepal, 2014) and the post-disaster needs assessment (PDNA) (GFDRR, 2013) has provided relevant approaches to pave the way for the SFDRR.

2.4.4.1 Indirect damage due to ripple effects in complex systems

The need to consider other types of damage as well as damage to multiple systems stems from the recognition that real events are much more complex than the representation of physical damage to few assets. Cascading effects, enchained failures, malfunctions of critical lifelines and inaccessibility to facilities and affected areas may be more severe in terms of impact and victims than the physical damage itself (Park et al., 2013). This can be considered as the systemic facet of indirect damage due to the interconnection and interdependency of urban and regional systems as well as among components of complex systems (Pitilakis et al., 2014).

As for systemic aspects, there have so far been few and partial attempts to model them to make them part of a more complete risk assessment (Bruneau et al., 2003). The MATRIX (2013) and the Syner-G (2014) projects can be recalled here, in particular with reference to the work done on modelling lifeline disruption due to natural disasters. By analysing in detail the models provided by both projects, it is evident that even though they are rather formalised, expert decisions must be provided at crucial nodes in order to run them. This is consistent with the fact that there is not enough statistical evidence for each type of malfunction of complex lifeline systems to allow for a more general formalisation of the evaluation procedure. In fact, until recently, only anecdotic narrative was available, accompanied by a few numerical figures. Few written reports regarding damage suffered by lifelines in case of floods are available (Pitt, 2008; Ministère de l'écologie, 2005). As for earthquakes, only recently the EERI reports providing first reconnaissance analysis of events have introduced a more in-depth section on lifelines. For the volcanic risk a rather interesting work has been conducted upon observations for a few eruptions, e.g. the Puyehue-Cordón Caulle 2011 eruption in Chile (Wilson et al., 2013; Craig et al., 2016; Elissondo et al., 2016) and the Shinmoedake 2011 eruption in Japan (Magill et al., 2013). Such efforts have not produced the number and extensive data available for physical damage, yet they represent an important first step that would require more focus on future efforts of collecting and analysing post- disaster damage data.

2.4.4.2 Indirect economic damage

Even less evidence is available for indirect damage on economic systems induced by direct damage, lifelines failures, and losses due to business interruption. Such damage and losses include induced production losses suffered by suppliers and customers of affected companies, the costs of traffic disruption or the costs of emergency services. Evidence to date suggests that indirect damage is more important in big disasters than in more trivial ones. For example, Hallegatte (2008) demonstrates that significant indirect loss for the state of Louisiana only arises when direct losses exceed EUR 50 billion. In a separate study, he also demonstrates that indirect impacts are greater if a natural disaster affects the economy during the expansion phase of its business cycle than if it touches it during a recession phase (Hallegatte et al., 2007).

Systemic interconnections and complexity of modern societies require new approaches of damage analysis and representation with respect to the ones that have been in use so far. Post-event damage assessment can provide key knowledge regarding multiple types of failures and indirect damage and loss.

Compared to direct physical effects, indirect economic losses are much more difficult to measure. Additionally, there are limited available sources of data for measuring indirect losses. It seems that defined and agreed-upon protocols for identifying and collecting useful data in this domain are still missing or are still in their early stages. Insurance data on business interruption are of limited value for that purpose, as most indirect effects, for example power outage, do not qualify for compensation under business interruption insurance. Moreover, insurance data must be indexed by insurance market characteristics (e.g. market penetration and average deductibles) to allow correct data interpretation and cross-country investigations. Also, until recently, most insurance companies tended to treat this data as private asset.

The limitation of accessible primary data have led to attempts to measure indirect losses using economic models of the type that have long been utilised for economic forecasting, such as:

- simultaneous equation econometric models (Ellison et al., 1984; Guimares et al., 1993; West and Lenze, 1994),
- input-output models (e.g. Rose and Benavides, 1997; Boisevert, 1992; Cochrane, 1997),
- computable general equilibrium models (Brookshire and McKee, 1992; Boisevert, 1995).

Studies evaluating model-based estimates (Kimbell and Bolton, 1994; Bolton and Kimbell, 1995; West, 1996) show that models developed for traditional economic forecasting tend to overstate the indirect effects. Differences to observed impacts from post- event economic surveys are by 70 % to 85 % (West and Lenze, 1994). The reason for this overestimation of both indirect regional economic losses from natural disasters and indirect regional economic gains from reconstruction is that statistically based economic models have been designed primarily to forecast the effects of a lasting impact.

The historical interlinkages embodied in these models are likely to be substantially disturbed and temporarily changed during a disaster. Dynamic adjustment features such as recovery, resilience, interregional substitution, inventory adjustments, changes in labour supply, number of displaced, etc. are not reflected in these models. In short, these models must be substantially revised in order to produce reliable estimates of indirect effects. Computational algorithms modelling supply shocks, post- event supply constraints and time- phased reconstruction in disaggregated spatial settings (as, for example, applied in van der Veen and Logtmeijer, 2005 and Yamano et al., 2007) seem promising to overcome this methodological gap.

2.4.4.3 Changes needed to improve post-disaster damage and loss data availability and quality

In order to obtain a more comprehensive and satisfactory overview of damage to assets, systems and sectors following a disaster, more consistent and systematically gathered data to address the complexity of real events are needed. Furthermore, as already suggested by the World Meteorological Organisation guidelines (2007), efforts of data collection should be reiterated in the same areas in order to detect trends that cannot be seen a few hours or days after the event and to monitor the rehabilitation and recovery process.

To achieve such a goal of obtaining and maintaining a more robust repository of different types of damage to multiple sectors, a standardised reporting system, similar to the PDNA or to the so- called Retour of Experience in France (Direction territoriale Méditerranée du Cerema, 2014) would provide significant advantages. First, because they will permit comparison between cases across geographic regions and time; it will then be easier to recognise similarities among cases and aspects that are specific to each case. Second, data collected and processed in the same way for key variables will allow us to obtain statistical evidence for some variables that at present are described only in a qualitative way. Third, more comprehensive and comparable reports will permit the building of a body of knowledge on different types of damage to several sectors that can support decision-making for a more resilient recovery and to feed pre-event modelling, as suggested in Figure 2.14.

2.4.4.3.1 Costs versus physical damage

Another field that would require substantial advancement relates to the reconciliation between different ways of representing damage and losses. Engineers generally provide a physical representation of damage in terms of affected buildings, bridges, lifelines and plants (and related components). Costs of asset repair or substitution can then be estimated. It is less easy than generally perceived to find an exact match between the estimated repair and substitution costs and the real expenses that are declared for the reconstruction of the same items (Comerio, 1996). This can be due to the fact that costs of amelioration are included too or that, if not governed, the process may lead to some distortions where someone takes undue advantage of the disaster. Extra costs may be due also to the excessive amount of needed repair material or workers from other areas to be recruited as local capacities are overwhelmed.

Furthermore, there are spatial and temporal scale issues that cannot be neglected; for example, the shift from individual items that are assessed to entire sector categories, like the shift between individual residential buildings to residential land uses. For an attempt of alignment, one may consider the recent work carried out by Amadio et al. (2015).

More comprehensive post-event damage analysis will provide fundamental knowledge to a variety of stakeholders. Innovation is needed to reconcile the 'engineering' representation of the physical damage and the economic assessment of direct and indirect damage and loss

The economic damage, however, is not restricted to the translation of physical damage or services malfunction into monetary terms. Instead, it reflects the economist's perspective, according to which loss goes beyond repair and reconstruction needs and comprises the total effect the damage will have on a given economy (either local or national) in terms of lost resources and assets (Pesaro, 2007).

Such resources can be linked to material damage, to business and service interruption or to the fact that customers will be lost as a consequence of prolonged businesses' interruption, etc. Systemic effects due to the failure or malfunction of lifelines and services can be described in terms of numbers (days/hours of interruption, number of customers without service) or in terms of the economic loss that has been caused by such a failure. The two representations of damage and losses do not fully coincide; instead it would be very important to find correspondences between them.

2.4.5 Conclusions and key messages

Partnership

A stronger partnership among a variety of stakeholders is required to achieve a more comprehensive and realistic picture of complex disasters' impact on society. Despite claims related to the usefulness of risk models for decision-making, researchers devoted attention to models that were already satisfactorily developed and to sectors for which it was relatively easy to get data (Grandjean, 2014). In fact, the focus of many scientific studies is improving the quality and the reliability of models, independently of completeness in terms of covered sectors and types of item. Completeness is important, however, for decision-makers. Local and regional governments are certainly interested in assessing not only the potential physical damage to buildings and a limited number of assets, but also the larger systemic effects, potential disruption of services and businesses and overall impacts on the regional economy. Depending on whether their role is managing prevention or emergencies, they are keen to know which sectors deserve more resources to reduce future risk and how expected damage will be distributed in space and in time.

Insurers are also interested in enhanced damage modelling and in a wider view of impacts that may shape the environment in which the damage they will have to compensate for occurs. In fact, duration of interruption is a crucial factor, particularly for businesses. In recent years, insurance companies have become more active in supporting their customers after an event to reduce such a duration. Knowing in advance what 'external factors' may impact on the capacity to return to normal operations will allow us to better tailor advice for mitigation that is increasingly recognised as part of insurers' work to diminish their own financial exposure.

Ultimately, we conclude that improved risk models supported by larger and more refined evidence derived from the observation of what actually happens after real events is for the benefit of risk mitigation measures, be they structural or non -structural.

Knowledge

The potential benefits for risk modelling that may be provided by enhanced damage data collection and analysis is still an open issue for both academic researchers and practitioners. Following a review of existing methods of damage modelling in Europe and the United States, Hubert and Ledoux (1999) had already suggested that post -event surveys may provide more 'reality' to assessments by subtracting the field of imagined and hypothesised damage and providing more evidence from observed and surveyed damage. They suggest this is necessary, particularly for those sectors such as lifelines and industries, for which risk models are still in their infancy in terms of robustness and completeness. In fact, as shown in this chapter, knowledge is more advanced in the field of direct physical damage to certain assets, in particular buildings, while less so with respect to other sectors and different types of damage.

Innovation

Multiple innovations are needed to enhance our capacity for damage modelling . First, there is the need to substantially improve post- disaster event and damage data collection and analysis (Barredo, 2009) to account for the different types of damage to multiple sectors that are currently missing. Second, there is a need to reconcile different interpretations of damage, not only in terms of definitions, a field where significant advances have been achieved, but also in terms of adopted units of measure and methods to aggregate cost at different scales.

Closer interaction between engineers, volcanologists, geophysicists, geographers and economists has to be sought in order to understand the implications and the links between different ways of accounting for and reporting damage and loss. This would permit an advancement of risk modelling by overcoming the apparent randomness of current assessments, which for some risks and for some assets are provided as damage index, and for others as costs.

Also, a more comprehensive framework considering spatial and temporal scales should be adopted in risk assessment. As for the former, it would be established looking at the chain of potential impacts, physical and systemic, and the quality and quantity of exposed elements and systems (including economic systems). Therefore, damage should not be considered only in the core area, where most physical damage has occurred, but case by case in the area of relevance, which can range from local to global in some extreme instances (Nanto et al., 2011). As for the temporal scale, it is key to reiterate the data collection at time intervals relevant for the type of event that has occurred. This will help to provide risk assessments with a clearer timestamp. A shift from a static representation of damage, defined in a pre-assigned time (often not made explicit), to more dynamic representations is necessary to show how damage changes and what type of damage becomes more prominent at each stage of the disaster event (impact, emergency or recovery).

2.5 Where are we with multihazards, multirisks assessment capacities?

Jochen Zschau

2.5.1 Why do we need a change in the way we assess natural risks?

2.5.1.1 Multirisk assessment versus single-risk assessment for disaster risk management

A given location on Earth may be threatened by more than one hazard. One of the challenges of disaster risk management (DRM) is to prioritise the risks originating from these different hazards to enable decisions on appropriate and cost-effective mitigation or preparedness measures. However, comparability between risks associated with different types of natural hazards is hampered by the different procedures and metrics used for risk assessment in different hazard types (Marzocchi et al., 2012). A common multirisk framework is needed being designed around a homogeneous methodology for all perils. In addition, many of the natural processes involve frequent and complex interactions between hazards. Examples include the massive landslides triggered by an earthquake or floods and debris flows triggered by an extreme storm event.

Risk globalisation and climate change are great challenges that require a shift in the way we assess natural risks from a single-risk to a multirisk perspective.

The chain of events — referred to as cascade or domino effects — can increase the total risk, and the secondary events may be more devastating than the original trigger, as shown in the 2004 Indian Ocean tsunami or the 2011 tsunami in Japan (Zschau and Fleming, 2012). Even independent events, if they occur at the same time and at the same place (e.g. hurricanes and earthquakes), may generate greater loss than the sum of totally separated single events.

The consequences of disastrous events are often propagated through the human-made system, causing interrelated technological, economic and financial disruptions, which may also result in social and political upheavals on all spatial scales. Even worldwide economies could potentially be disrupted by major disasters through their impact upon global supply chains (Zschau and Fleming, 2012). In addition, the impact of one hazard may increase the potential harmful effect of another hazard. For example, by changing vegetation and soil properties, forest fires may increase the probability of debris and flash floods (Cannon and De Graff, 2009). Similarly, a building's vulnerability to ground shaking may increase due to additional structural loads following volcanic ash fall or heavy snowfall (Lee and Rosowsky, 2006; Zuccaro et al., 2008; Selva, 2013). Vulnerability in these cases would be highly time variant.

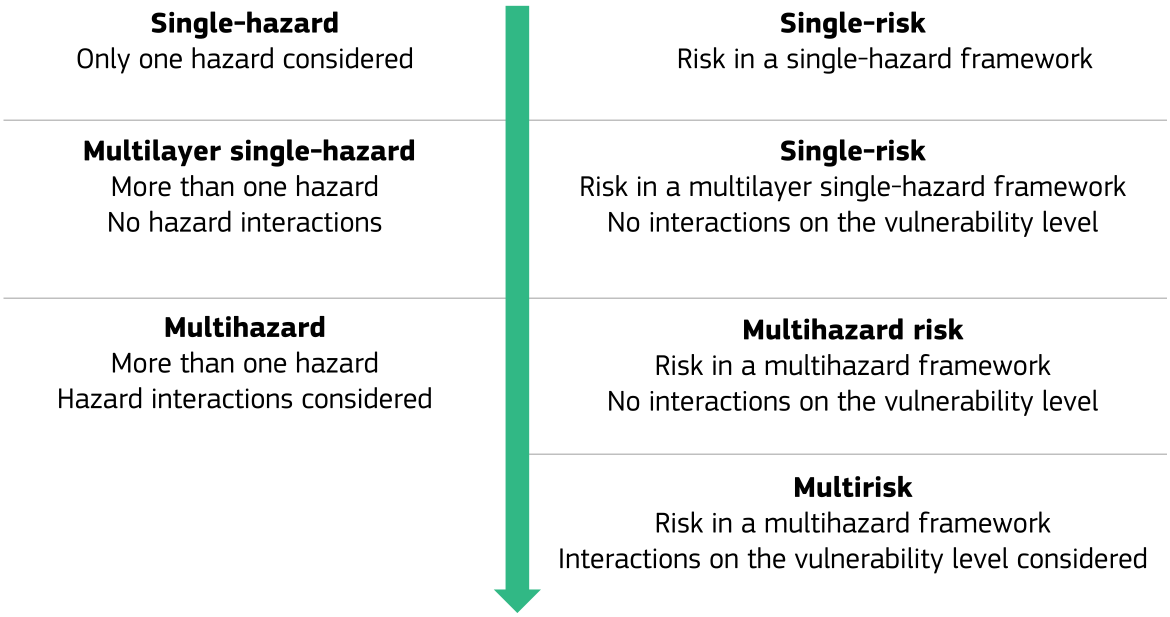
Multihazard risk approaches start from single-hazard risk assessments. Figure 2.19 attempts to capture the transition from single-hazard to multihazard risk as well as the definitions used. Single-hazard risk is the most common method.

2.5.1.2 Emerging challenges: risk globalization and climate change

The risks arising from natural hazards have become globally interdependent and, therefore, not yet fully understood. The ongoing 'urban explosion', particularly in the Third World, an increasingly complex cross-linking of critical infrastructure and lifelines in the industrial nations as well as an increasing vulnerability due to climate change and growing globalisation of the world's economy, communication and transport systems, may play a major part (Zschau and Fleming, 2012, Gencer, 2013). These factors are responsible for high-risk dynamics and also constitute some of the major driving forces for disaster risk globalisation. Communities are affected by extreme events in their own countries and become more vulnerable to those occurring outside their national territories. The effects of a destructive earthquake in Tokyo, for instance, may influence London through shaky global markets and investments; or a disaster in a global city such as Los Angeles may affect developing economies like Mexico and can put the already vulnerable poor into further poverty (Gencer, 2013). In addition, the increased mobility of people can spatially enlarge the scale of natural disasters. This was demonstrated, for example, by the fatal tsunami disaster of 2004 along the coasts of the Indian Ocean, where the victims did not only come from the neighbouring countries, but included nearly 2 000 citizens from Europe, for instance, most of whom had been visiting resorts in the affected region during their Christmas holidays when the tsunami struck. Globalisation is not

FIGURE 2.19

From 'single-hazard' to 'multirisk' assessment and terminology adopted here.
Source: courtesy of author



the only reason for the growing interdependencies and the high dynamics seen in the risks from natural hazards. Climate change may be another important factor. According to IPCC (2014), it is very likely that extreme events will occur with higher frequency, longer duration and different spatial distribution. Climate change is also projected to increase the displacement of people, which will lead to an increase of exposure to extreme events. They will be exposed to different climate change impacts and consequences such as storms, coastal erosion, sea level rise and saltwater intrusion (Nicholls and Cazenave, 2010).

A multirisk modelling approach will be required in order to capture the dynamic nature and various interactions of the hazard and risk-related processes driven by both climate change and globalisation. Moreover, the sought-after solutions for risk assessments are no longer exclusively aiming at the best possible quantification of the present risks, but also at keeping an eye on their changes with time and allowing to project these into the future.

2.5.2 Towards multirisk assessment methodology: where do we stand?

2.5.2.1 Sources of our present knowledge: the role of EU-funded projects

The Agenda 21 for Sustainable Development (UNEP, 1992), the Johannesburg Plan for Implementation (UN 2002), the Hyogo Framework for Action (UNISDR, 2005) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) promote multihazard risks of natural hazards. Together with the International Decade for Natural Disaster Reduction (IDNDR) from 1990 to 1999 and the following permanently installed International Strategy for Disaster Reduction (ISDR), they constitute a worldwide political framework for the initiation of a multitude of scientific projects in the risk research community (Zentel and Glade, 2013). These projects include global index-based multihazard risk analysis such as Natural Disaster Hotspots (Dilley et al., 2005) or INFORM (De Groeve et al., 2015). They also include regional multihazard initiatives like the cities project for geohazards in Australian urban communities (Middelmann and Granger, 2000), the Risk Scape project in New Zealand (Schmidt et al., 2011) and the platforms HAZUS (FEMA, 2011) and CAPRA (Marulanda et al., 2013) for the automated computation of multihazard risks in the United States and Central America, respectively.

The European Union funded projects on multihazard and multirisk assessment within its framework programmes FP4, FP5, FP6 and FP7. The TIGRA project (Del Monaco et al., 1999) and the TEMRAP project (European Commission, 2000) were among the first attempts to homogenise the existing risk assessment methodologies among individual perils. The European Spatial Planning Observation Network (ESPON) compiled aggregated hazard maps weighting the individual hazards by means of expert opinion and taking into account various natural and technological hazards in Europe (Schmidt-Thomé, 2005).

A multirisk assessment framework should allow for the comparison of risks and account for dynamic vulnerability as well as complex chain reactions on both the hazard and vulnerability levels

Quantitative, fully probabilistic methods for multihazard and multirisk assessment were developed in a series of FP6 and FP7 projects: Na.R.As. 2004-2006 (Marzocchi et al., 2009), ARMONIA 2004-2007 (Del Monaco et al., 2007) and MATRIX 2010-2013 (Liu et al., 2015). Their results allow independent extreme events (coinciding or not coinciding) as well as dependent ones, including cascades, to be treated on both the hazard and the vulnerability levels. Moreover, these projects have time-dependent vulnerability taken into account. Their methods were applied in the CLUVA project 2010-2013 to future projections of the influence of climate change on natural hazards and urban risks in Africa (Bucchignani et al., 2014; Garcia-Aristizabal et al., 2015 a, b, 2016) as well as in the CRISMA project 2012-2015 to crisis scenario modelling for improved action and preparedness(Garcia-Aristizabal et al., 2014).

In addition, projects in Europe funded on a national or regional basis have contributed significantly to our present knowledge on multirisk assessment. The German Research Network for Natural Disasters (DFNK), which had undertaken comparative multirisk assessments for the city of Cologne (Grünthal et al., 2006), gives an example of this. The Piedmont region project in Italy, with a focus on a methodological approach for the definition of multirisk maps (Carpignano et al., 2009), and the ByMuR project 2011-2014 on the application of the Bayesian probabilistic multirisk assessment approach to natural risks in the city of Naples (Selva, 2013) are two other examples. Furthermore, the Centre for Risk Studies of the University of Cambridge in the United Kingdom is presently one of the first to systematically address the globalisation aspect of risk. The centre is currently setting up a global threat taxonomy and a risk assessment framework aiming at macro-catastrophe threats that have the potential to cause large-scale damage and disruption to social and economic networks in the modern globalised world (Coburn et al., 2014).

2.5.2.2 Multilayer single-risk assessments: harmonisation for risk comparability

In order to assist decision-makers in the field of DRM in their prioritising of mitigation actions, one has to understand the relative importance of different hazards and risks for a given region. This requires the threats arising from different perils to be comparable with each other. However, this is difficult, because different hazards differ in their nature, return period and intensity, as well as the effects they may have on exposed elements. Moreover, the reference units, such as ground acceleration or macroseismic intensity for earthquakes, discharge or inundation depth for floods and wind speed for storms, are different among the hazards. This does not only hamper the comparability between the threats, but it also makes it difficult to aggregate the single perils in a meaningful way in order to assess the total threat coming from all the hazards in a region. These problems exist independently of whether hazard interactions and/or interactions on the vulnerability level are important or not. Thus, to overcome them, and as a first step towards a full multirisk assessment, one may treat them in the context of a multilayer single-hazard/risk assessment approach, ignoring the interactions but harmonising and standardising the assessment procedures among the different perils.

Three major standardisation schemes can be distinguished in this context (Kappes et al., 2012; Papathoma-Köhle, 2016). They make use of:

- matrices — hazard matrix, vulnerability matrix and risk matrix;
- indices — hazard index, vulnerability index and risk index; and
- curves — hazard curves, vulnerability curves and risk curves.

They are applicable on all three assessment levels: hazard, vulnerability and risk, respectively.

Matrices

A hazard matrix applies a colour code to classify certain hazards by the intensity and frequency (occurrence probabilities) determined qualitatively, for instance 'low', 'moderate' and 'high (Figure 2.20). Based on this, one can compare the importance of hazards and one may derive the overall hazard map by overlaying the classification results of all single hazards. An example of this approach is the risk management of natural hazards in Switzerland (Figure 2.20, redrawn from Kunz and Hurni, 2008; see also Loat, 2010). The European Commission-funded Armonia project (Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment) has proposed a similar classification scheme (Del Monaco et al., 2007). Likewise, the French risk prevention plans (Cariam, 2006) follow this kind of approach.

Like in the 'hazard case', overarching matrix schemes also exist on the vulnerability level. So-called damage matrices, for example, are discrete approaches to vulnerability assessment that oppose relative damage or damage grades to classified hazard intensities in a matrix. The resulting vulnerability (fragility) is either qualitatively described (few, many or most), for instance as the proportion of buildings that belong to each damage grade for various levels of intensity (see Grünthal, 1998 in relation to the European macroseismic scale), or quantitatively described as the probability to reach a certain damage grade (Tyagunov et al., 2006).

For the aim of comparing and aggregating risks coming from multiple hazards, assessment procedures are required that combine both hazard and vulnerability information. Various authors (e.g. Sterlacchini et al., 2007; Sperling et al., 2007; Greiving, 2006) have suggested matrix schemes that fulfil this requirement. The European Commission (2010) proposed a risk matrix that relates the two dimensions, likelihood (probability) and impact (loss), for a graphical representation of multiple risks in a comparative way (Figure 2.21). Distinct matrices were suggested for human impact, economic and environmental impact and political/social impact, as these categories are measured with distinct scales and would otherwise be difficult to compare.

Indices

Apart from the matrix-based approaches described above, index-based approaches are another means to achieve comparability in the multilayer single-hazard and -risk context. The methodology of composite indicators allows to combine various indicators to obtain a meaningful measure.

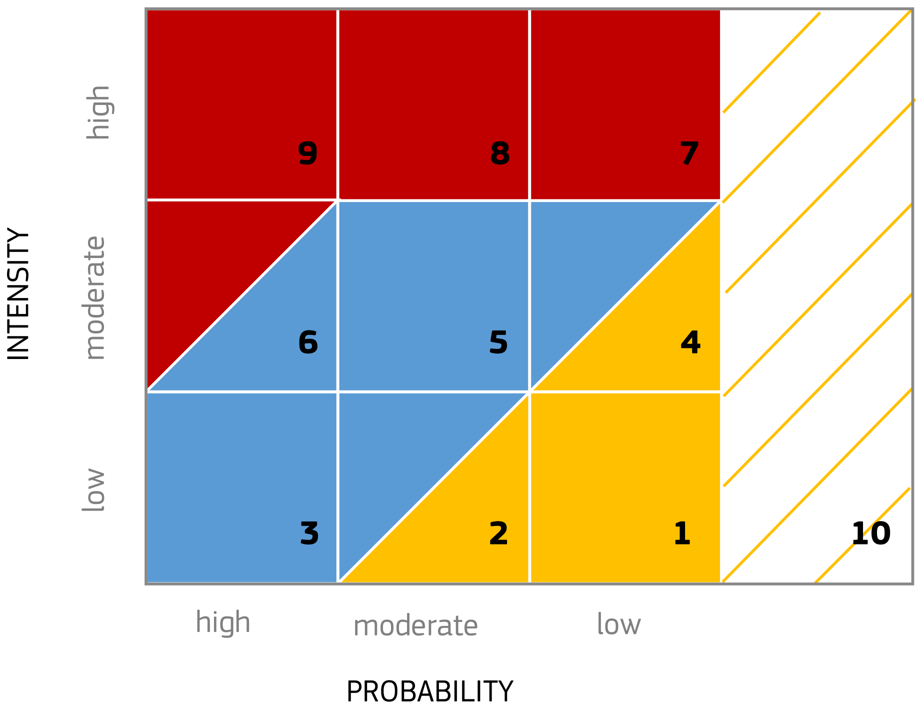
An example of an index-based approach on the hazard level is global Natural Disaster Hotspots (see also Chapter 2.5.2.1), which is an aggregated multihazard index calculated from the exposure of a region to various hazards and is used to identify key ‘hotspots’, where the exposure to natural disasters is particularly high. A more recent example was put forward by Petitta et al. (2016) who suggested a multihazard index for extreme events capable of tracking changes in the frequency or magnitude of extreme weather events.

Vulnerability indices (see also Chapter 2.3) are already widely used in the socioeconomic field, including multihazard settings, as for example in the studies of Wisner et al. (2004), Collins et al. (2009) and Lazarus (2011), but they are rarely hazard specific (Kappes et al., 2011). In contrary , physical vulnerability is regarded as hazard- specific. An increasing number of studies is now available that applies hazard-specific vulnerability indicators to, for instance, tsunamis (Papathoma et al., 2003), floods (Barroca et al., 2006, Balica et al., 2009; Müller et al., 2011), landslides (Papathoma-Köhle et al., 2007; Silva and Pereira, 2014) and mountain hazards (Kappes et al., 2011). In various cases the indicators are combined with the PTVA (Papathoma Tsunami Vulnerability Assessment) method (Papathoma and Dominey-Howes, 2008).

Going from vulnerability indices to risk indices is another solution to achieving comparability in the multilayer single-risk context. As a risk indicator includes hazard information in addition to vulnerability information, such a step also allows the aggregation of the risks coming from different perils. Dilley et al. (2005), who computed hazard and vulnerability for natural hazards on a global scale and weighted the hazard with the vulnerability index to calculate risk, gave an example. For the derivation of the multihazard risk, all single-hazard

FIGURE 2.20

Swiss hazard matrix
Source: Kunz and Hurni (2008)



risks were added up.

All three levels of an index-based approach, i.e. the hazard, vulnerability and risk levels, are addressed in the ongoing European project INFORM (see also Chapter 2.5.2.1), where separate indices for hazard and exposure, vulnerability, lack of coping capacity and risk are developed in order to identify countries where the humanitarian crisis and disaster risk would overwhelm national response capacity.

Curves

More quantitative methods for assessing natural threats in a multilayer single-hazard approach are based on 'curves' ('functions').

Hazard curves present the exceedance probabilities for a certain hazard's intensities in a given period. Vulnerability curves graphically relate the loss or the conditional probability of loss exceedance to the intensity measure of a hazard (for instance ground motion, wind speed or ash load) in order to quantify the vulnerability of elements at risk. When the probability of exceeding certain damage levels is considered, the curves are referred to as 'fragility curves'.

One may easily combine vulnerability curves with the corresponding hazard curves to arrive at a measure of risk. This could be the average loss per considered period, the so-called average annual loss or expected annual loss, if the period is 1 year. It could also be a risk curve, which graphically relates the probability of loss exceedance within the period under consideration to the loss coming from all possible hazard intensities. As exceedance probabilities and loss are not expressed in hazard-specific units, they are directly comparable among different hazards and can easily be aggregated to an overall multilayer single risk.

Figure 2.22 shows the annual exceedance probability of direct economic loss from earthquakes, floods and storms in the city of Cologne (Grünthal et al., 2006). Storms turn out to be the dominant risk at return periods lower than 8years (largest loss!). Floods take over for higher return periods up to 200 years and earthquakes become the dominant risk for return periods higher than 200 years.

A comparison between the risks from the different perils can be accomplished based on the expected average loss within the considered period represented by the area under the risk curve (Van Westen et al., 2002).

Fleming et al. (2016) demonstrated that one may also easily aggregate the single-hazard-specific risk curves to obtain a 'total risk' curve without considering potential interactions between the hazards. Figure 2.23 shows the wind, storm and earthquake risks for the city of Cologne. The various aggregations of the risk probabilities, for instance for loss in the order of EUR 100 million, indicate enhanced loss probabilities from between 15 % and 35 % for the individual hazards and up to 56 % in 50 years when combined.

FIGURE 2.21

Risk matrix proposed by the European Commission
Source: European Commission (2010)

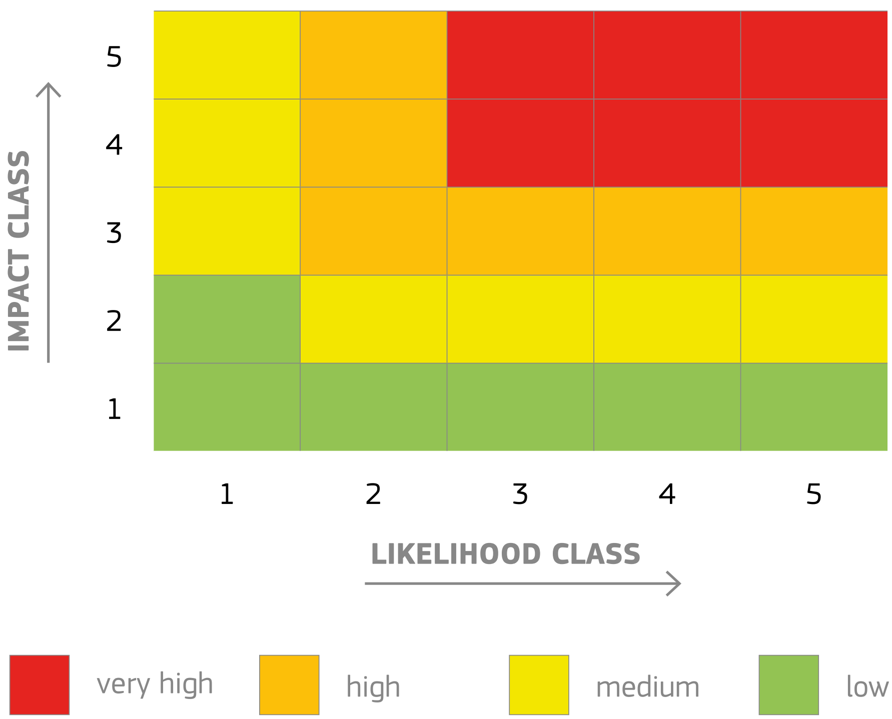


FIGURE 2.22

Risk curves for the city of Cologne
Source: Grünthal et al. (2006)

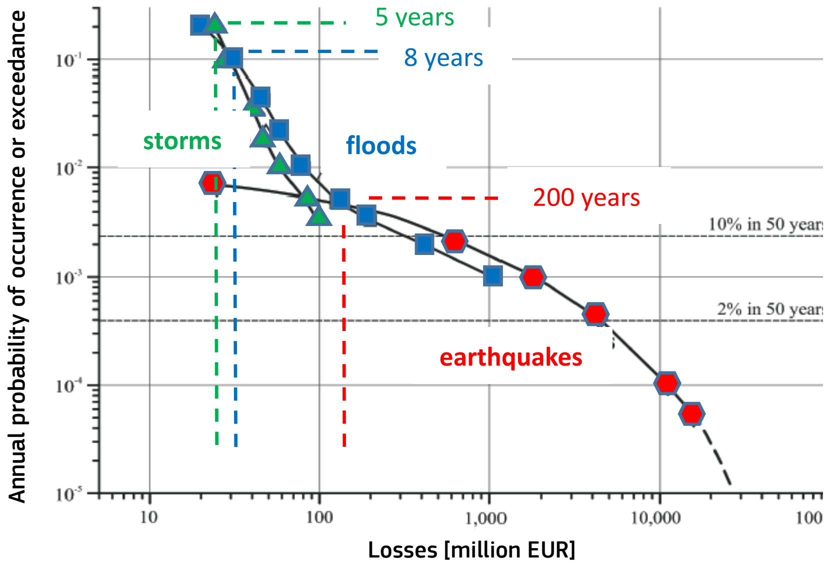
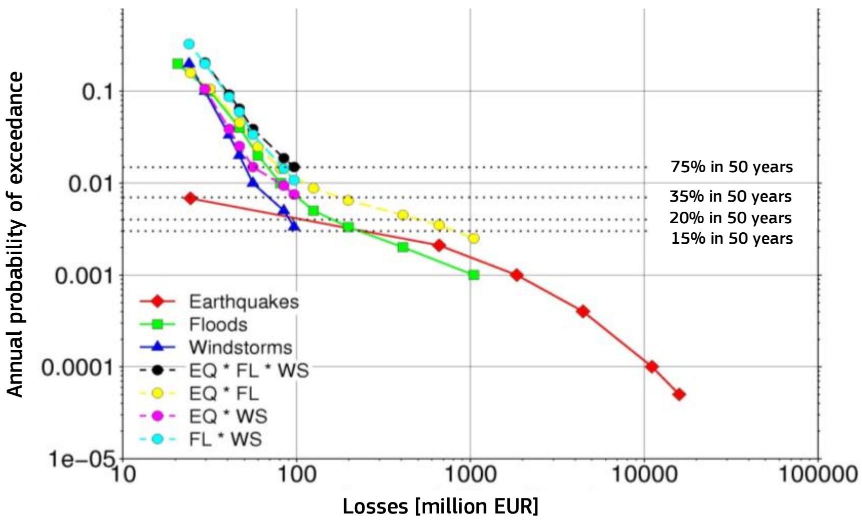


FIGURE 2.23

Risk curves and their aggregations for the city of Cologne
Source: Fleming et al. (2016)



Hazard, vulnerability and risk curves are the quantitative equivalent to the hazard, vulnerability (damage) and risk matrices. On the other hand, there is a distinct difference between them: the curves only make use of two dimensions, frequency and impact, to characterise risk, whereas matrices use three dimensions, by additionally introducing colour codes. The third dimension expresses different levels of risk from 'low' to 'high' with different colours, which gives extra weight to either the impact or the likelihood (see, for instance, Figure 2.21).

This is an added value of risk matrices, since the additional colour code makes it possible to compare high-probability and low-consequences events with low-probability and high-consequences ones, for instance. To extract similar information from risk curves, probabilities and loss can simply be multiplied (P×L). The lines of equal loss–probability products, P×L, in a logarithmic risk curve plot would be straight diagonal lines (Figure 2.24, left). In the case of a single-risk scenario with a given annual probability, the loss-probability-product directly represents the average annual loss (impact). This is not the case for the risk curve, which includes the loss from all possible hazard intensities. However, one may easily show that in this case it represents the contribution to the average annual loss per increment of logarithmic probability. Thus, from additionally displaying the exceedance probability as a function of the loss-probability-product instead of the loss alone, one may learn which part of the risk curve, in terms of return periods, will contribute most to the average annual loss. In the case of Cologne (Figure 2.24, right), storms and floods contribute the most in the range of small return periods, whereas for earthquakes the return periods of around 1 000 years have the highest contribution to the average annual loss.

The probabilistic concept of risk curves is used for both economic losses of a potential disaster and the indirect, socioeconomic impacts, as long as these are tangible. As examples, Garcia-Aristizabal et al. (2015a) mention losses in work productivity, losses due to missing income, costs of evacuation and the costs of medical assistance as well as effects of the loss of functionality of systems and networks including disruptions of productivity and the means of production. Garcia-Aristizabal et al. (2015a) also describe how the information from the socioeconomic context can be integrated straightforwardly into the quantitative multi-layer risk framework by harmonizing the metrics of the different loss indicators and producing the single loss exceedance curves and their sum, respectively, equivalent to the methodology used for direct losses. However, this needs to introduce quantitative vulnerability/fragility information for each of the different indicators or even their respective vulnerability/fragility curves, which still is the bottleneck of the method.

2.5.2.3 Hazard interactions: cascading events and Co.

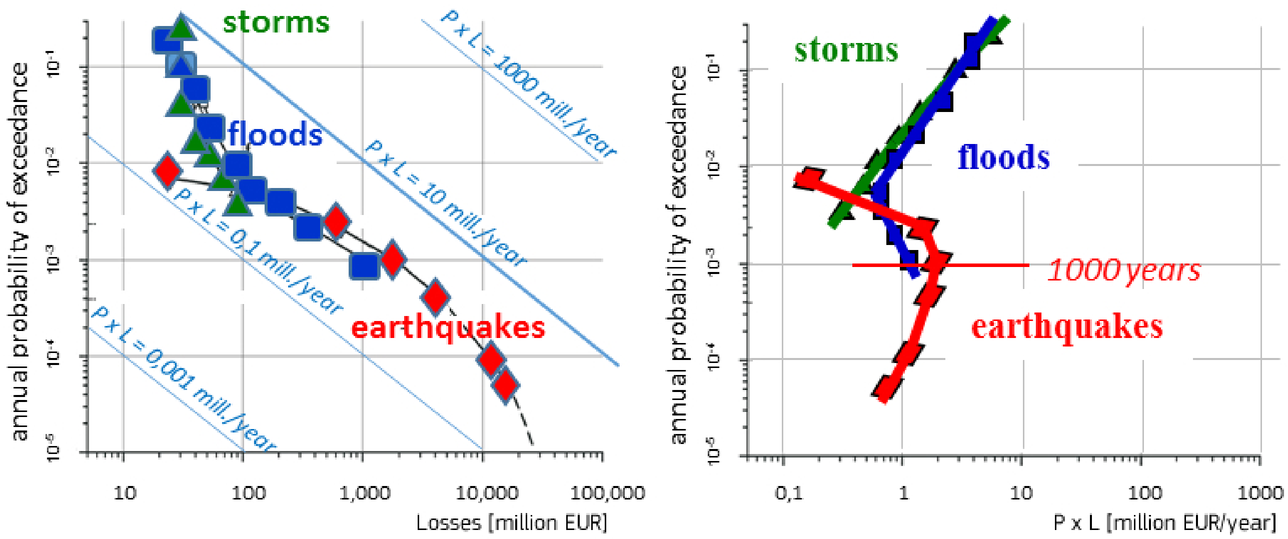
Multilayer single-risk assessments, as described in the previous section, analyse the risks coming from different perils separately. Assuming independence between the hazard-specific risks, they simply add them up to obtain the overall hazard in a region. However, in a complex system like nature, processes are very often dependent on each other, and interact. There are various kinds of interactions between hazards that often lead to significantly more severe negative consequences for the society than when they act separately. A multilayer single-risk perspective does not consider this, but a multihazard approach does.

Classification of hazard interactions

The complexity of interactions between hazards has led to a multitude of terms in use for describing different types of interdependencies. The term 'cascades' has been used, for instance, by Carpignano et al. (2009), Zuccaro and Leone (2011), Choine et al. (2015) and Pescarol and Alexander (2015); 'chains' by Xu et al. (2014), among others; and 'interaction hazard networks' by Gill and Malamud

FIGURE 2.24

Risk curves and P x L - curves for the city of Cologne (Exceedance probability versus loss (left) and versus its product with loss (right)
Source: courtesy of author



(2016). Further terms in use are 'coinciding hazards' (Tarveinen et al., 2006; European Commission, 2010), 'coupled events' (Marzocchi et al. 2009), 'domino effects' (Luino, 2005), 'follow-on events' (European Commission, 2010) and 'triggering effects' (Marzocchi et al., 2009). More of such terms are presented and explained in Kappes et al. (2012).

Gill and Malamud (2014, 2016) suggested classifying the different hazard interaction types into five groups (Box 1). In the first group, the 'triggering relationship', the secondary (triggered) hazard, might be of the same type as the primary (triggering) one or different, for instance an earthquake that triggers another one or a rainfall event that triggers a landslide, respectively. In the second group, the 'increased probability relationship', the primary hazard, does not directly trigger a secondary event but changes some aspects of the natural environment, leading to an increase of the probability of another hazard. For instance, in the event of a wildfire, vegetation is destroyed, which can result in an increased vulnerability of a slope to landslides (Gill and Malamud, 2014). In the third group, 'decreased probability relationship', the probability of a secondary hazard is decreased due to a primary hazard (third group), therefore it does not pose a problem to risk management. Gill and Malamud (2014) gave the example of a heavy rainfall event that increases the surface moisture content, whereby reducing the depth to the water table and consequently decreasing the probability of a wildfire. Similarly, the spatial and temporal coincidence of events, the 'coincidence relationship' (fourth group), may be considered as some kind of interaction, because although independent of each other, together they can increase the impacts beyond the sum of the single components if the hazards had occurred separately in time and space. An example can be seen in the coincidence of the Mount Pinatubo volcano eruption in 1991 with Typhoon Yunya (Gill and Malamud, 2016), where the combination of thick and heavy wet ash deposits with rainfall triggered both lahars (Self, 2006) and structural failures (Chester, 1993). In the fifth group, the 'catalysis/impedance relationship' between hazards, a triggering relation between two hazards may be catalysed or impeded by a third one. A volcanic eruption, for instance, can trigger wildfires, but this triggering interaction may be impeded by a tropical storm.

Furthermore, anthropogenic and technological hazards may interact with natural hazards, not only by the trigger and increased probability relationships, but also by catalysis/impedance relationships. These may include, for example, storms impeding an urban fire-triggered structural collapse or storm-triggered floods, which are catalysed by a blocking of drainage due to technological failures.

Based on geophysical environmental factors in the hazard-forming environment, Liu et al. (2016) proposed a different classification scheme for hazard interactions by distinguishing between stable environmental factors, which form the precondition for the occurrence of natural hazards, and trigger factors, which determine the frequency and magnitude of hazards. Dependent on these environmental factors, one may divide the hazard relationships into four classes: independent, mutex (mutually exclusive), parallel (more than one hazard triggered in parallel) and series relationships (one hazard follows another). Classification schemes for hazard interactions help to ensure that all possible hazard interactions among different hazards are considered in a

BOX 2.1

Classification of hazard interactions

Source: Gill and Malamud (2014, 2016)

(1) Triggering relationship
(2) Increased probability relationship
(3) Decreased probability relationship
(4) Coincidence relationship
(5) Catalysis/ impedance relationship

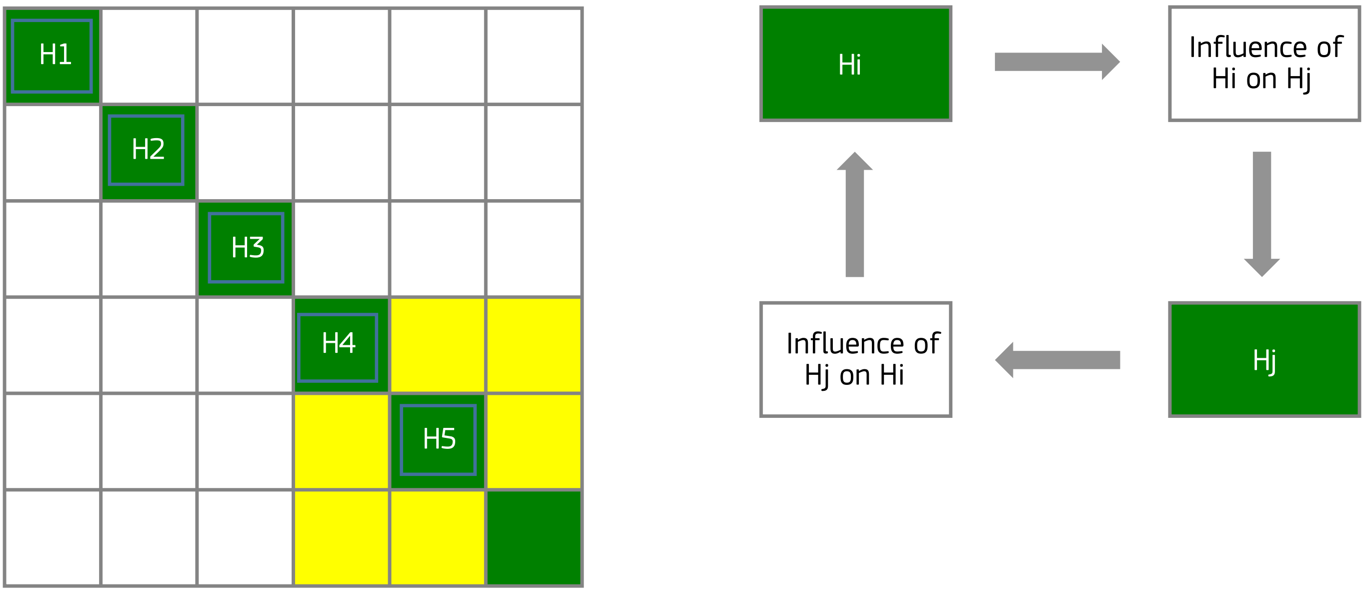
multihazard risk assessment (Liu et al., 2016).

Methods

Among the available methods to integrate hazard interactions into disaster risk assessment, there are qualitative, semi-quantitative and quantitative ones. Qualitative methods settle for qualitative descriptions and classifications of interactions with the aim of identifying the most important hazard relations in a region. Semi-quantitative approaches are mainly based on so-called hazard-interaction matrices (not to be confused with the hazard matrix addressed in Chapter 2.5.2.2). They offer a structured approach to examine and visualise hazard interactions and to see how strong these interactions are, aiming not only at the identification of important hazard relations but also at getting insight into the evolution of the system when different hazards interact. This kind of matrix has been used, for instance, by Tarvainen et al. (2006), De Pippo et

FIGURE 2.25

Matrix approach for the identification of hazard interactions.
Source: Liu et al. (2015)



Slides (H4)	2	2
0	Debris flows (H5)	2
1	1	River floods (H6)

0 – No interaction

1 – Weak interaction

2 – Medium interaction

3 – Strong interaction

Slides (H4)	Deposits only	Cut off a flow in a water course
No interaction	Debris flows (H5)	Change of river bed morphology
Erosion / saturation of deposits	Re-mobilisation of deposits	River floods (H6)

al. (2008), Kappes et al. (2010), Gill and Malamud (2014), Mignan et al (2014) and Liu et al. (2015). Figure 2.25 gives an example of how this matrix approach can be used in multihazard assessment: first, the matrix is set up in a way that all potentially interacting hazards in the region under consideration are occurring in the matrix's diagonal (Figure 2.25a). The possible interactions are described in a clockwise scheme (Figure 2.25b), which results in the influences of a hazard on the system appearing in the related matrix row and the influences of the system on the hazard in the hazard's column (Figure 2.25c). In addition, a coding between 0 and 3 is used (Figure 2.25d) to semi-quantitatively describe how strong the interactions are between the different hazards, respectively, and are entered into the matrix (Figure 2.25e). Liu et al. (2015) propose this scheme to be used as second level in their three-level framework from qualitative to quantitative multirisk assessment in order to decide whether it is justified to go to the third quantitative level of assessment or not.

Gill and Malamud (2014) have used a similar kind of matrix to characterise the interaction relationships between 21 natural hazards, both qualitatively as well as semi-quantitatively. This matrix identifies and describes hazard relations and potential cascades as well as characterises the different relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard in both the triggering and increased probability cases. Moreover, they were able to indicate the spatial overlap and temporal likelihood of each triggering relationship.

Quantitative methods for integrating hazard interactions into disaster risk assessment are mainly based on event tree and fault tree strategies (see the event tree example in Figure 2.26 for volcano eruption forecasting) combined with probabilistic approaches for quantifying each branch of the tree. Among them, the concept of Bayesian event trees, where the weight assigned to a branch of a node in the tree is not a fixed single value but a random variable drawn from a probability distribution function, is of particular interest. It allows the rigorous propagation of uncertainties through the different computation layers when simulating all the hazard relations in a complex chain. The event tree structure (Newhall and Hoblitt, 2002; Marzocchi et al., 2004, 2008, 2010; Selva et al., 2012) is particularly suitable for describing scenarios composed by event chains. Neri et al. (2008), for instance, compiled a probability tree for future scenarios at the volcano Mount Vesuvius, including various eruption styles and secondary hazards associated with them. Marzocchi et al. (2009, 2012) also employed a probabilistic event tree to analyse triggering effects in a risk assessment framework. Moreover, Neri et al. (2013) used a probability/scenario tree for multihazard mapping around the Kanlaon volcano in the Philippines. However, the available quantitative studies in this field that explicitly consider hazard interactions remain rare (Liu et al., 2015).

The probabilistic framework to be combined with an event tree strategy for quantifying hazard interactions has been discussed in Marzocchi et al. (2004, 2008, 2010 and 2012); Selva (2013); Garcia-Aristizabal and Marzocchi (2013); Gasparini and Garcia-Aristizabal (2014); and Garcia-Aristizabal et al. (2015a). It is equivalent to the probabilistic framework for the multilayer hazard assessment introduced in Chapter 2.5.2.2, where the single hazards are quantified by their hazard curves, respectively, and are combined with vulnerability curves to obtain the probability of potential loss. The difference, however, is that in the case of interactions between two perils, the secondary hazard's probabilities for all possible intensity scenarios will form a hazard surface rather than a hazard curve (Figure 2.27).

So far, vulnerability has been considered as static. Like exposure, vulnerability is also highly dynamic regardless of whether it is physical, functional or socioeconomic

This is because the probability of a hazard event that has been affected by another one depends on the intensities of both the primary and secondary events.

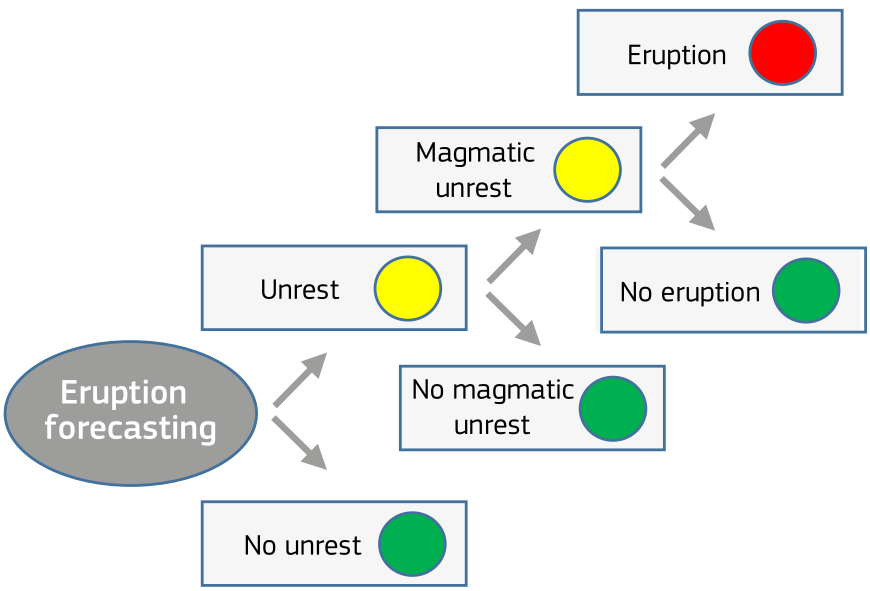
Long-term event databases on a certain hazard may already contain the secondary events arising from interactions with other primary hazards (Marzocchi et al., 2012). Hence, for long-term problems, e.g. when the tsunami hazard over the next 50 years is to be assessed, there is no need to apply a multihazard methodology. A multilayer single hazard one would do, as was demonstrated by Garcia-Aristizabal et al. (2015b) with regard to future projections of the climate-related triggering of floods, drought and desertification in the area of Dar es Salaam (Tanzania) until 2050. However, in the short term (e.g. hours to days), for instance, when heavy rain changes the landslide occurrence probability in a time horizon of a few days, a multihazard approach is necessary to account for this interaction.

Marzocchi et al. (2012) also gave a simple example showing how the adoption of a single-hazard perspective instead of a multihazard one could be misleading in a short-term problem. Their example addresses the possible collapse of a pipe bridge in the Casalnuovo municipality in southern Italy, which has an increased probability, when volcanic activity triggers heavy ash loads. The collapse in an industrial centre could cause an explosion and subsequent air and water contamination. In this example it appeared that one would underestimate the probability of a pipe bridge collapse and, hence, the industrial risks (explosion, contamination) that might follow from it by more than one order of magnitude, if the secondary ash loads from volcanic activity were neglected.

A full hazard curve to quantify hazard interactions is still rare, although Garcia-Aristizabal et al. (2013) have shown that this is possible when they presented hazard curves for volcanic swarms and earthquakes triggered by volcanic unrest in the region of Naples.

FIGURE 2.26

Event tree scheme for eruption forecasting
Source: Selva et al. (2012)



Application to climate change

Based on the concept of risk curves above, it is not immediately visible the extent to which the probabilistic framework is also suitable for treating the interactions of climate change with natural hazards. The reason is that the framework has its origins in stationary processes, whereas an impact of climate change on natural hazards, resulting in more or less gradual changes regarding the hazards' frequencies and their intensity extremes, represents a non-stationary process. The methodology applied to it has to account for this (see, for instance, Solomon et al., 2007; Ouarda and El Adlouni, 2011; Seidou et al., 2011, 2012). The problem is rendered even more difficult by the fact that the probabilities of future extremes could be outside the data range of past and present observations and, hence, we cannot draw on experience, i.e. on existing data catalogues. A solution to the problem comes from extreme value theory, as this theory aims at deriving a probability distribution of events at the far end of the upper and lower ranges of the probability distributions (Coles, 2001), where data do not exist or are very rare.

The generalised extreme value distribution, combined with a non-stationary approach (the so-called non-stationary GEV model), is therefore, widely applied today to predict the effects of climate change on meteorological hazards. Examples are El Adlouni et al. (2007) and Cannon (2010) for precipitation, Siliverstovs et al. (2010) for heat waves, Seidou et al. (2011, 2012) for floods and Garcia-Aristizabal et al. (2015b) for extreme temperature and precipitation. How this approach can be integrated into the above probabilistic framework for multihazard and multihazard risk assessment was demonstrated by Garcia-Aristizabal (2015b), who succeeded in harmonising the outcome of the non-stationary GEV model application to Dar es Salaam in Tanzania in the form of time-dependent, high-resolution probabilistic hazard maps and hazard curves.

2.5.2.4 Dynamic vulnerability: time- and state-dependent

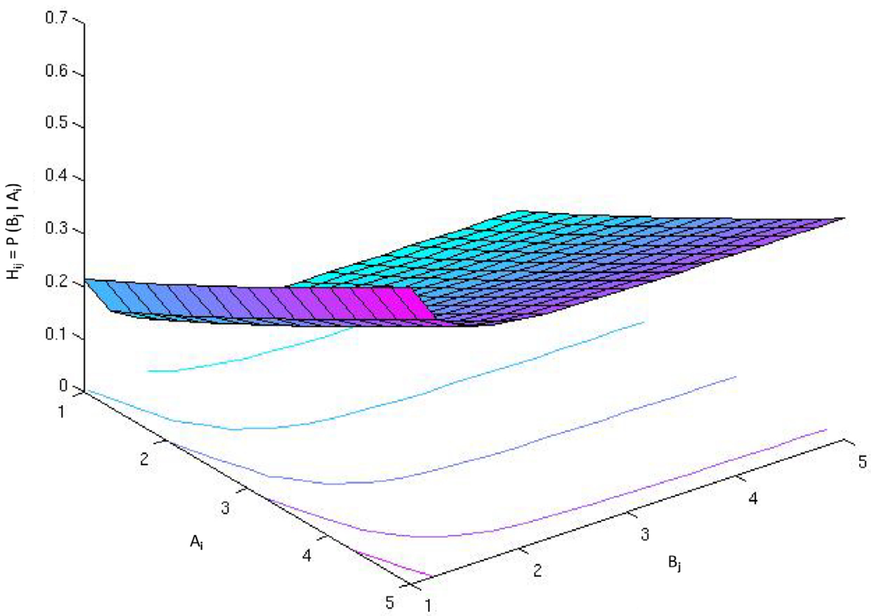
The different types of vulnerability dynamics

One may distinguish between two types of vulnerability dynamics, the time-dependent and the state-dependent one. In the first, we refer to more or less gradual changes of vulnerability with time. In the second, vulnerability depends on a certain state of a system that may change abruptly, due to a natural hazard event, for instance. If a load on a system (e.g. snow on a roof) determines the relevant vulnerability state, the expression would be 'load-dependent vulnerability'; if it is about a pre-damage state (e.g. a building that has been pre-damaged by a seismic main shock and threatened by aftershocks), the term 'pre-damage-dependent vulnerability' is employed.

The term 'time-dependent vulnerability' is used in the engineering community for distinguishing between the gradual deterioration of a building's fragility due to corrosion and the abrupt changes when an earthquake strikes.

FIGURE 2.27

Example of a hazard surface, Hij, describing hazard interaction as a probability surface that depends on all possible intensities, Ai and Bj, of the primary event 'A' and of the secondary event 'B', respectively
Source: Garcia-Aristizabal and Marzocchi (2013)



Time-dependent vulnerability

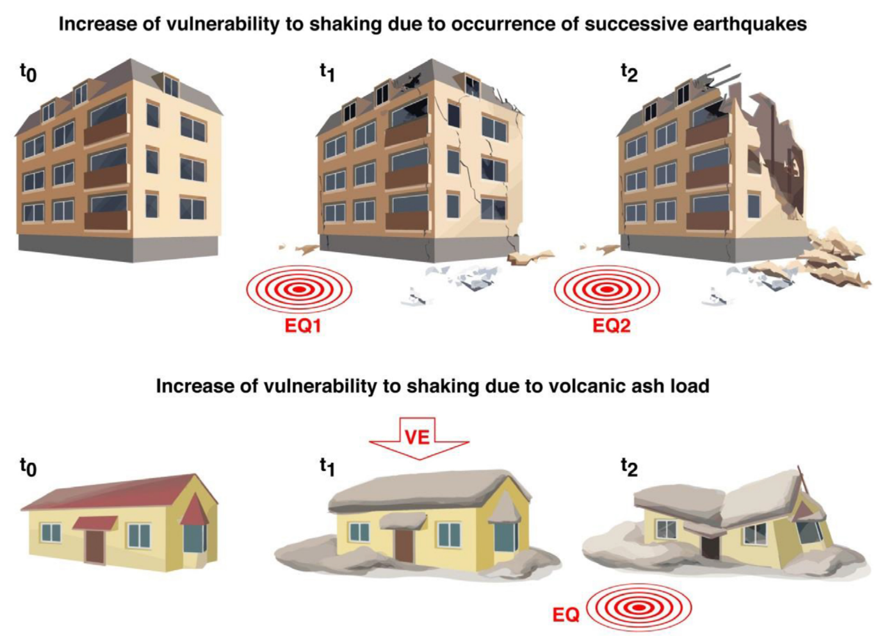
Time-dependent vulnerability dynamics may have many origins, depending on the problem under consideration and the dimension of vulnerability involved, i.e. social, economic, physical, cultural, environmental or institutional (for the dimensions of vulnerability see Birkmann et al. 2013). Vulnerability changes due to the ageing of structures, for instance, have been addressed by Ghosh and Padgett (2010), Choe et al. (2010), Giorgio et al. (2011), Yalcinev et al. (2012), Karapetrou et al. (2013) and Iervolino et al. (2015 a), among others. Münzberg et al. (2014) pointed to power outages, where the consequences and hence the vulnerability of the public may progressively change within hours or days. Moreover, Aubrecht et al. (2012) made short-term social vulnerability changes in terms of human exposure in the diurnal cycle subject of discussion. In the long term, especially when regarding the possible effects of climate change and globalisation over the next decades, the interacting social, economic and cultural factors will probably be the most important drivers of vulnerability dynamics. These include demographic, institutional and governance factors (IPCC, 2012; Aubrecht et al., 2012; Oppenheimer et al., 2014). Some of them could be related to the rapid and unsustainable urban development, international financial pressures and increases in socioeconomic inequalities, as well as failures in governance and environmental degradation (Oppenheimer et al. 2014).

State-dependent vulnerability

The more abrupt state-dependent vulnerability changes occur when two hazards interact on the vulnerability level and the first one alters the exposure or the state of exposed elements in a way that changes the response of the elements to the second one. This second event may or may not be of the same hazard type as the former, and is either independent or dependent on the first one. An example for load-dependent vulnerability can be found in Lee and Rosowsky (2006), who discussed the case of a wood-frame building loaded by snow and exposed to an earthquake. Accordingly, Zuccaro et al. (2008), Marzocchi et al. (2012), Garcia-Aristizabal et al. (2013) and Selva (2013) gave the example of the seismic vulnerability of buildings loaded by ash due to volcanic activity (Figure 2.28, below). In addition, Selva (2013) presented an example for state-dependent exposure. In this case, strong local earthquakes changed the exposure to a tsunami by people escaping from their damaged buildings and concentrating in seaside areas, which is where tsunamis hit. Pre-damage-dependent seismic vulnerability/fragility is important for earthquake aftershock risk assessment (Figure 2.28, above) and so has been addressed by Bazurro et al. (2004), Sanchez-Silva et al. (2011), Polese et al. (2012, 2015) and Iervolino et al. (2015a, 2015b), among others.

FIGURE 2.28

Two examples of state-dependent seismic vulnerability: pre-damage-dependent vulnerability (above) and load-dependent vulnerability (below)
Source: Mignan (2013)



Integration into a probabilistic framework

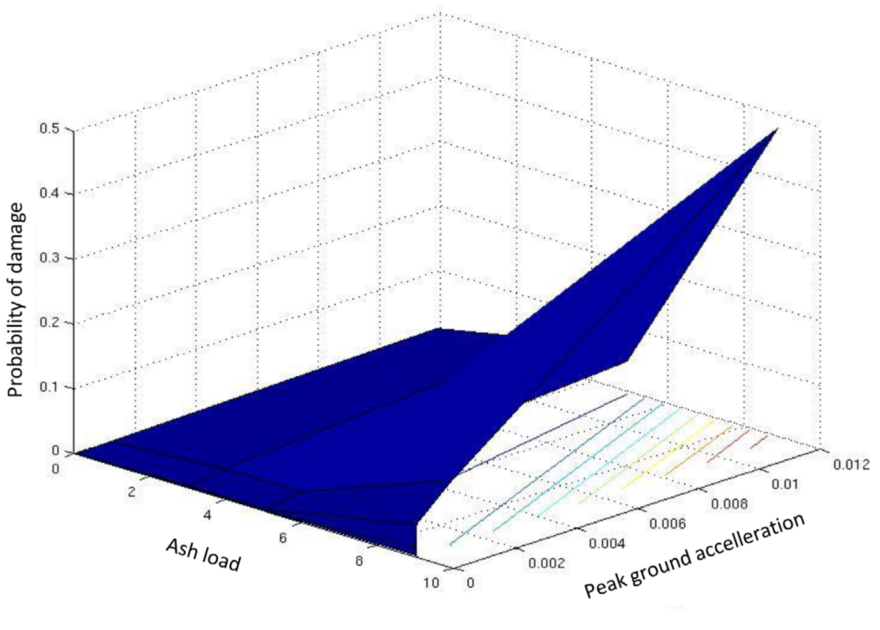
In the case of the ageing of structures, whereas one may easily integrate time-dependent vulnerability into a probabilistic multirisk assessment approach, for instance by means of time-dependent fragility functions (see Ghosh and Padgett, 2010; Karapetrou et al., 2013), this is not the case for the long-term vulnerability changes relevant to climate change and globalisation. Despite the existence of a few studies in the climate change research community that have made an attempt to project probabilistic risk curves into the future (e.g. Jenkins et al., 2014), the use of vulnerability/fragility curves does not seem to be common. According to Jurgilevich et al. (2017), the main bottleneck in assessing vulnerability and exposure dynamics and projecting them into the future is poor availability of data, particularly for socioeconomic data. Another bottleneck relates to the uncertainty and accuracy of the projections. Whilst one might have data about the future population, these data are often useless for assessing the future levels of education, income, health and other important socioeconomic aspects. This may be the reason why vulnerability assessments are still mostly based on present socioeconomic data, whereas current climate change projections go up to the year 2100 (Cardona et al., 2012). In light of the significant uncertainties involved in future projections of vulnerability, climate change-related literature has suggested the production of a range of alternative future pathways instead of one most plausible vulnerability scenario (Dessai et al., 2009; Haasnoot et al., 2012, O'Neill et al., 2014, among others). Still, dynamics of vulnerability or exposure are presently only included in half of the future-oriented studies related to climate change. Moreover, the inclusion of dynamics in both is observed in less than one third of the studies oriented to the future (Jurgilevich et al. 2017).

Following Garcia-Aristizabal and Marzocchi (2013), Garcia-Aristizabal et al. (2015 a) and Gasparini and Garcia-Aristizabal (2014), the situation is different for the pre-damage- and load-dependent vulnerabilities. One may easily integrate them into a probabilistic multirisk approach by extending the above framework for multilayer single-risk and multihazard risk assessment to account for hazard interactions on the vulnerability level.

The main difference of such an extended multirisk approach compared to the former one is the fact that vulnerability/fragility is introduced into the multirisk framework as a vulnerability/fragility surface instead of a curve (see Figure 2.29). This is because vulnerability, in the case of these interactions, depends on both the variable state of the exposed elements as well as on the intensity of the secondary event. In the case of load-dependent fragility/vulnerability, a load, for instance an ash load due to volcanic activity (see the fragility surface in Figure 2.29), determines the variable state of the exposed elements. For pre-damage-dependent fragility/vulnerability, the load parameter of the fragility/vulnerability surface is substituted by a parameter describing the pre-damage state.

FIGURE 2.29

Ash load-dependent, two-dimensional seismic fragility surface
Source: Garcia-Aristizabal and Marzocchi (2013)



In order to get a feeling of how different the results of the multirisk approach can be from those of the single-risk approach, let us take the example of seismic risk in the Arenella area of Naples, which was modified by ash loads. Garcia-Aristizabal et al. (2013) found that, in this case, the expected loss from earthquakes was remarkably sensitive to the thickness of an ash layer from volcanic activity assumed to load the roofs of the area's buildings. Whereas for a 24-cm ash layer the expected loss from earthquakes increased by less than 20% compared to the case without load, it reached an amplification factor of six for a 41-cm thick layer.

A simple example demonstrating what the effect of pre-damage-dependent vulnerability may quantitatively amount to can be deduced from the damage- and pre-damage-dependent fragility curves provided by Abad (2013) for a hospital in Martinique (French West Indies). For a ground motion of 5 m/s2 at the building's resonance, the probability of reaching a damage state 4 (near to collapse or collapse) is found from their curves to be roughly 7 % if pre-damage is not accounted for. On the other hand, assuming a pre-damage state 3 on a scale up to 4 results in a collapse probability of more than 30 %, an increase of nearly a factor of five.

Iervolino et al. (2015b), among others, have extended the concept of pre-damage-dependent vulnerability to account for the accumulation of damage in a series of aftershocks. Moreover, Sanchez-Silva et al. (2011) and Iervolino et al. (2013, 2015a) proposed to take into account both age-dependent and state-dependent vulnerabilities in one model of the time-variant failure probability of structures.

Matrix city

The 'Matrix city' framework, proposed by Mignan et al. (2014) for a quantitative multihazard and multirisk assessment that accounts for interactions on both the hazard and the vulnerability levels and considers time-dependent vulnerability, is conceptually quite different from the one introduced so far. It consists of a core simulation algorithm based on the Monte Carlo method. This method simulates a large number of stochastic hazard-intensity scenarios, thereby allowing for a probabilistic assessment of the risk and for the recognition of more or less probable risk paths. As each scenario is represented by a time series, the method is also appropriate for assessing the risks associated with non-stationary processes, such as the hazards and/or vulnerabilities under climate change. Intra- as well as interhazard intensity interactions are introduced by a so-called hazard correlation matrix.

This matrix is of the same type as the hazard interaction matrix used by Gill and Malamud (2014) for qualitatively and semi-quantitatively characterising interaction relationships between natural hazards, but by entering the one-to-one conditional probabilities of the secondary hazards it is applied in a quantitative way. For creating a hazard/risk scenario, the Monte Carlo method draws the probabilities from a Poisson distribution. So far, Matrix city has only been used with generic data to demonstrate the theoretical benefits of multihazard and multirisk assessment and to show how multirisk contributes to the emergence of extremes. It has been successfully tested, but 'identifying their real-world practicality will still require the application of the proposed framework to real test sites' (Mignan et al., 2014).

2.5.3 Implementation of MRA into DRM: Present state, benefits and barriers

2.5.3.1 State of implementation

Multirisk is not systematically addressed among DRM in EU countries (Komendantova et al., 2013a, 2013b, 2014, 2016; Scolobig et al., 2013, 2014a, 2014b). Single-hazard maps are still the decision support tool most often used in DRM, even more often than single-risk maps. Along with the missing link between scientific multirisk assessment and decision-making in DRM comes a general lack of integrated practices for multirisk governance.

2.5.3.2 Expected benefits

The practitioners involved in the Matrix study emphasised the following benefits:

- ranking and comparison of risks.
- Improvement of land-use planning, particularly as the multirisk approach provides a holistic view of all possible risks. It may influence decisions about building restrictions, which themselves may influence urban and economic planning, for example by regulating the construction of new houses and/or economic activities.
- Enhanced response capacity, because a multirisk approach would allow planning for potential damage to critical infrastructure from secondary events and preparation for response actions.
- Improvements in the efficiency of proposed mitigation actions, cost reductions, encouraging awareness of secondary risks and the development of new partnerships between agencies working on different types of risk.

2.5.3.3 Barriers

Barriers to effectively implementing multirisk assessment into DRM are found in both the science and practice domains as well as between them. In addition, individual perceptual and cognitive barriers may play a role in both domains (Komendantova et al., 2016).

Barriers in the science domain mainly relate to an unavailability of common standards for multirisk assessment across disciplines. Different disciplines use different risk concepts, databases, methodologies, classification of the risk levels and uncertainties in the hazard- and risk-quantification process. There is also an absence of clear definitions of terms commonly agreed across disciplines, including the term 'multirisk' itself, for which there is no consensus as regards its definition. These differences make it hard for various risk communities to share results, and hence represent a barrier to dialogue on multirisk assessment.

A lack of quantitative information on the added value of multirisk assessment is perhaps more worrying for risk managers than for scientists. The risk managers who participated in the Matrix study pointed out that there are not enough quantitative multirisk scenarios or their comparisons with single risk ones available from which they could learn about the added value of multirisk. Furthermore, they miss criteria or guidelines that would help them to select the scenarios to be included in a multirisk assessment. Most worrying for them, however, seem to be the strong limitations quantitative multirisk assessment methods, in their opinion, have when one regards their user friendliness. According to them, a high degree of expertise is often required to use the scientific tools, resulting in a restriction of their application to only a narrow number of experts.

Multirisk is presently not systematically addressed among DRM in EU countries. The barriers to the implementation of MRA include a lack of agreed definitions

Moreover, poor cooperation between institutions and personnel, especially when risks are managed by authorities acting at different governmental levels, was identified as a major reason for a lack of integrated practices for multirisk governance in the practical domain (Scolobig et al., 2014a). Decentralised and centralised governance systems have their own weaknesses and strengths in this regard (Komendantova et al., 2013a; Scolobig et al., 2014b). Furthermore, in some cases a multirisk approach is perceived as competing with rather than complementing single-risk approaches. The Matrix study also argued that in many European countries the responsibility for DRM has steadily been shifted to the local level (often to the municipal level) without providing sufficient financial, technical and personnel resources for implementing necessary programmes (Scolobig et al., 2014a). This is a clear obstacle for implementing multirisk methodologies.

Finally, there are individual cognitive barriers to implementing multirisk assessment approaches into the DRM decision-making processes, i.e. barriers related to how people perceive the problem of multirisk. Komendantova et al. (2016) presented the case of the 1995 Kobe earthquake in Japan, where the hazard was underestimated, simply because large earthquakes had been absent during the previous decades. Similar consequences are observed when building codes for earthquake-resistant structures are not followed, a problem that still exists all over the world, including in Europe. Individual cognitive barriers may only be overcome by raising awareness.

Overcoming these barriers will require a long-term commitment on behalf of risk modellers and officials as well as strong partnerships for a 'step-by-step' approach to progressively implementing multirisk methodology into practice.

2.5.4 Conclusions and key messages

Partnership

A better integration of scientific knowledge of multirisk assessment into developing policies and practices will require a long-term commitment from both sides, science and practice, and building new partnerships between them. Such partnerships should enhance the knowledge transfer between science and practice and, among others, should help involve practitioners as well as their requirements in the scientific development of multirisk methodology at an early stage. Common efforts will be particularly necessary for simplifying existing methods for practical use. Furthermore, scientists are asked to provide practitioners with more scenarios demonstrating the added value of multirisk assessments in various situations, and together they should collaborate in establishing criteria for appropriate scenarios to be included in a multirisk assessment.

More specifically, it might also be worthwhile considering the common development of a multirisk rapid response tool for assessing potential secondary hazards after a primary hazard has occurred. As lack of data is a crucial weakness in multirisk assessments, partnerships should also extend their collaboration to sharing data and building common integrated databases, in particular for demographic, socioeconomic and environmental data.

Such partnerships could be realised with common projects or by creating so-called multirisk platforms for common methods and data, and/or establishing so-called local multirisk commissions, institutional areas with an interdisciplinary and multisector character for discussing and acting on multirisk issues.

Knowledge

Although a theoretical framework for multirisk assessment and scenario development is in place, there is still a need for further harmonisation of methods and particularly terms across the scientific disciplines. Moreover, more quantitative scenarios on present and future risks in a multirisk environment are needed, particularly with regard to potential indirect effects and chain-shaped propagations of damage into and within the socioeconomic system. Such scenarios are still rare, mainly because of two reasons. First, the comprehensive databases needed for a multirisk assessment either do not exist, are not freely available or are insufficient; there is a need for establishing such databases between the disciplines. Second, quantitative fragility/vulnerability information, in particular fragility/vulnerability curves and surfaces, respectively, have so far been developed only for a few specific cases, mostly related to the direct impact of a disaster, but hardly to its indirect consequences; these, however, in many cases may be more important than the direct ones.

Therefore, the scientific knowledge base needs to be extended to quantitative vulnerability information, vulnerability curves and surfaces for indirect disaster impacts as, for instance, the loss in work productivity, loss of the functionality of systems and networks, costs of evacuation, costs of medial assistances and much more.

Innovation

A multi-risk modelling approach will be required in order to capture the dynamic nature and the various interactions of the hazard and risk related processes driven by both climate change and globalization. Moreover, solutions for risk assessments are needed that are no longer exclusively aiming at the best possible quantification of the present risks but also keep an eye on their changes with time and allow to project these into the future.

The future challenges have two dimensions, one focused on empowering good decisions in practice and another on improving our knowledge base for better understanding present and future risks

Developing an integrative model for future risk that considers not only the potential climate change-induced hazard dynamics, but also the potential dynamics of complex vulnerability components and the involved uncertainties will require the expertise of all these disciplines. A strong partnership will be required between the natural sciences, the social and economic sciences, as well as the climate change research community.

Recommendations

DRM requires a combination of skills knowledge and data that will not be held within one firm, one industry, one institution, one discipline, one country or even necessarily one region. Europe contains a concentration of expertise on DRM, perhaps unique in the world; the opportunities here are greatest and should be seized.

Historically, many in industry and the private and public sectors found it challenging to engage with academia. For example, industry often works within tight timescales, wanting to hear a single right answer with certainty, wanting dissemination of what is known now as opposed to new research and wanting it in a form that can be easily incorporated into existing models and processes not requiring detailed assessment, adjustment and review. But there is an increasing awareness of what science has to offer, which often leads to an even greater demand for collective engagement. This engagement has been encouraged by EU research projects encouraging public/private/academic linkages all involved in DRM, where practitioners, scientists and policymakers need to actively seek engagement with others working in the broad DRM space: within their organisation and within their sector, as well as more broadly. This is easy to say but rather more difficult to do.

Only positive interaction will make the practitioner aware of what is possible: what new data, models and techniques are available and how these may be adapted for practical use within their organisation or department. The practitioner lies in the centre of the process. It is they that understand the gaps of knowledge and data, where true value for additional research lies. But often unconsciously there may be 'group think' — an accepted way of working that is not adequately challenged. It is healthy to develop links with other practitioners in their field, in other sectors or industries and in academia. Increasing knowledge and expertise can be both a push and a pull: both learning from others and also using in-house expertise to drive knowledge for the common good.

Areas where other practitioners or academics may have valuable information include the fields of data, methodologies and models. Knowledge may be siloed: restricted to particular risks, hazard or exposure types. The practitioner is in a position to break down these silos, spotting where data or processes in one area may have value in another. This is particularly true when looking at the interaction of hazards, secondary hazards and non-physical impacts such as business interruption and broader economic loss.

It is important to learn from other sectors facing similar issues and learn from their experience. For example, methods have been developed in the insurance industry to model and manage catastrophe risk that can be applied almost directly to societal risk including to people, property and the environment. There are quick wins available; early adopters are not starting from a clean sheet but building on a framework that is already well founded. No innovation is risk free, but development of a risk management strategy for a city, for example; is based upon well-developed methodologies and so is very likely to deliver real value and be seen to deliver real value.

Science can respond to identified needs but only if it hears the call, as it were. Very often the need is not for new research but for directed application of what is known within academia, not elsewhere. Information and data need to be offered in forms that are accessible, appropriate and affordable. More work is required to build publicly available datasets and models (for example the global earthquake model initiative). Where governments hold data, it is important to balance the desire to exploit that data for profit against the greater good of making the information available to all those who can use it to develop tools that ultimately benefit and protect the broader European population.

Before embarking on a DRM project, like for any other project it is important to understand what the objectives of the project are: what needs to be done and when it needs to be done. DRM is an area where there is always a need for further understanding and knowledge in each of the three pillars of risk assessment: hazard, exposure and vulnerability. Each element requires different skills, different data and different techniques; the process can seem daunting. There are many real examples of best practice, methodologies, data sources and assessment and analytical techniques to act as a template. The process will not necessarily be smooth, but the process of developing understanding and awareness is arguably where the real value lies. It is important not to let the fear of lack of knowledge or data prevent this vital work from commencing. Innovative thinking is required to meet the challenges of a lack of data and partial information endemic in the process, for example new methods to assess exposure by remote sensing or vulnerability, particularly to economies and ecosystems. The challenge is to focus innovation on where it has the most value, a proper risk assessment process will provide a guide to where the greatest requirement for innovation and further research lies.

Risk assessment and analysis provides an objective basis against which policy decisions can be made and transparently justified and the cost and benefits of different strategies and options can be compared in an objective way, open to scrutiny and challenge. All models are assumption dependent, but it is important that the policymaker has some knowledge of the limitations of the modelling done and the key assumptions upon which it depends. The issue is balance: clearly a policymaker cannot be expected to be a risk management expert, but uncritically relying on one source of information can lead to political as well as practical risk — a culture of challenge and evidence- based analysis is required. It is important that policymakers are able to interpret the risk assessments given to them. European insurance regulators demand that directors of insurance companies are able to understand and defend risk assumptions and decisions made within the firm; they cannot hide behind the judgement of employees or consultants however well qualified. The same scrutiny is applied to policymakers and practitioners in the public sector who respond to disasters. Whilst not hiding behind experts, it is important that policymakers can demonstrate that appropriate expertise has been engaged and risk management decisions have been made firmly founded.

At its best, DRM not only adds to the information available to policymakers, but it also creates a new way of looking at risk within organisations. Risk management should not be seen as just the responsibility of a risk management department but should be understood by all those involved in decision-making. Embracing risk management and risk modelling has transformed the insurance industry in the last 30 years, making it infinitely more aware of the risks that it and its clients face and much more able to meet their needs (and pay their claims). It is a virtuous circle: greater knowledge feeds an understanding of what is missing and a drive to fill those gaps; it demands an engagement with academia, the adoption of best science and the development of best practice via interaction with other practitioners. The process of improvement becomes self-sustaining, increasing knowledge and understanding to the benefit of all. Europe demands better DRM, so the opportunity must be seized.

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Introduction

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Chapter 3

Understanding disaster risk: hazard related risk issues

SECTION I
Geophysical risk

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3 Understanding disaster risk: hazard related risk issues

Section I. Geophysical risk

CONTENTS

Introduction

Earthquakes and volcanic eruptions are the most hazardous geophysical processes that have their origin in the Earth's lithosphere (i.e. in the outermost solid part of the Earth). Both events are driven by common fundamental geodynamic procedures, namely the motion of the lithospheric plates and the resulting deformation that takes place, mainly at the plate boundaries but, on some occasions, in the interior of the plates too.

The largest and more frequent earthquakes occur without the involvement of volcanic activity. However, sometimes the latter is accompanied by strong earthquakes. Every year, thousands of people lose their lives due to large destructive earthquakes and volcanic eruptions. In addition, extensive loss of property, negative economic consequences, both tangible and intangible, as well as social disruption occur as a result of such events. Earthquakes may produce disastrous effects due to the ground shaking relatively close to their sources, say at distances of a few hundreds of kilometres at most. While volcanic eruptions produce multiple hazards, some of which, such as tephra fall, may cause disastrous results far away or even on a global scale.

When earthquakes and volcanic eruptions occur in submarine environments or close to coastal zones, the surface of the sea can be suddenly disturbed, thus generating large sea waves known as tsunamis. The catastrophic results produced by earthquakes and volcanic eruptions are often dramatically increased due to the associated tsunamis that may cause destruction at great distances from their seismic or volcanic sources. However, catastrophic tsunamis can be also generated from other processes, such as coastal or submarine landslides impacting the sea-water surface. Such landslides may be the result of gravity or ground shaking caused by earthquakes or volcanic eruptions.

Protecting population from geophysical risks such as earthquakes, volcanic eruptions and tsunamis, and mitigating the risks of such events is not an easy task because these phenomena are highly complex and usually unpredictable. Therefore, the assessment of their potential impact (i.e. the level of associated risks) is not a trivial procedure. However, the assessment of risk associated not only with these three types of geophysical processes but also with other types of natural hazards is characterised by some commonalities. The first is that one has to assess the level of hazard, in other words, to estimate some of the important elements or parameters of the phenomenon per se. For hazard assessment purposes of interest are the frequency of occurrence of the geophysical event (e.g. earthquake), in a given magnitude level and the probability to exceed or not to exceed this level in a given time interval. Depending on the probability model selected to apply the hazard assessment could be time independent or time dependent, the latter being more realistic but also less easy to apply. Another approach is to consider scenario-based hazard assessment, for example by selecting an extreme, a realistic or another scenario for the occurrence of the geophysical event in the future.

Both the probabilistic and the scenario-based hazard approaches are susceptible to a variety of uncertainties. Lack of knowledge and of data leads to epistemic uncertainly but the intrinsic uncertainty associated with the statistical perspective in order to understand the physical processes leads to the so-called aleatory uncertainty, which in practice is associated with randomness (Woo, 2010). Regardless of the method applied to estimate hazard, a common practice valuable for preparedness, risk management and decision-making is the preparation of suitable maps illustrating the level of the various types of hazards in a given area. For example, volcanic activity may threaten an area with various types of hazard, such as lava flows, tephra falls, etc. In such cases, the preparation of appropriate maps is needed to express the level of hazard of each type of hazard.

The assessment of hazard, however, is a representation of the phenomenon only and does not describe the expected impact of the geophysical events. For the estimation of the expected impact (risk), the vulnerability of the various assets that are exposed to the geophysical event should be taken into account (UNISDR, 2015). A wide range of vulnerabilities may be considered for population as well as for engineered structures (e.g. buildings) and other properties. But, again, the issue of time dependence is important. For example, levels of human exposure and vulnerability in a coastal zone threatened by tsunamis are quite different in the daylight hours of the summer season from those in the evening hours of the winter season. Eventually, for a qualitative or quantitative risk assessment, the results of the hazard, exposure and vulnerability assessments should be combined by applying techniques that depend on data availability. For better hazard assessment, the datasets regarding the record of the natural phenomena can be drastically improved with the expansion of the existing instrumental networks and other recording systems. Moreover, better socioeconomic data, such as those referring to populations and buildings, can help to improve risk components such as exposure and vulnerability.

The mitigation of risk can be achieved by a variety of actions that can be undertaken by decision-makers, civil protection authorities and other stakeholders. Of particular importance among these actions are the early warning systems (EWSs). These systems are composed of detection, monitoring of precursors and forecasting of probable event, analysis of risk, dissemination of meaningful and timely warnings or alerts of the possible extreme events and activation of emergency plans to prepare and respond. Some hazards are difficult to predict (e.g. earthquke) due to lack of knowledge, data or adequate measuring techniques of the precursors that lead to hazardous event. Early warning, however, takes place also when the event has already started. From the first recording stage and before the catastrophic culmination of the event, we may have some estimation of the maximum level of severity of the event and the expected time and location of its catastrophic stage. Other actions aiming to mitigate and manage risks may include preparedness, training, education and public awareness.
This chapter describes several recent developments across the different disciplines of earthquake, volcanic and tsunami risk assessment and highlights a multitude of resources currently available to the disaster risk reduction community.

3.1 Geophysical risk: earthquakes

Vitor Silva, *Mauro Dolce, Laurentiu Danciu, Tiziana Rossetto, Graeme Weatherill*

3.1.1 Earthquake sources and seismotectonic setting

3.1.1.1 Global distribution of earthquakes

The global distribution of earthquakes, as shown in Figure 3.1, is one of the key insights into the shape of the Earth's lithospheric plates and their direction of movement. The vast majority of earthquakes are generated at boundaries, where plates converge, diverge or move laterally past one another (Bird 2003). The greatest proportion of seismicity, and by far the largest proportion of seismic energy release, occurs in regions where lithospheric plates converge with one another. These convergent boundaries may manifest as regions of subduction, where an oceanic plate is forced beneath a less dense plate, that is, either a continental or a younger oceanic plate. In a convergent boundary between continental plates, tectonic compression may produce folding and faulting and shortening and thickening of the plates within the collision zone (orogenesis or mountain building). The Himalaya Mountain Range is an example of this type of convergent boundary. Both types of regional environments are characterised by regions of high seismic activity and host faults that are capable of generating very large earthquakes. In Europe, convergence between the European and African plates mainly results in a large belt of compression in the western Mediterranean and subduction in the Calabrian, Hellenic and Cypriot arcs of the Central-Eastern Mediterranean.

Divergent plate boundaries represent areas where the shallow crust is being pulled apart. These may manifest as rift zones, such as the East African Rift, where the shallow continental crust is undergoing extension, resulting in moderate to high seismicity and volcanism. Earthquakes greater in magnitude than M7 are rare in such environments. Nonetheless, extensional zones can be highly active and many areas, even those unrelated to divergent boundaries, such as the Apennines regions of central Italy or the Corinth Gulf, have seen repeated destructive earthquakes over the centuries. Transform and transcurrent plate boundaries manifest where the relative movement of plates is lateral.

Understanding past earthquakes and their impact on society is the first step to assess and eventually mitigate seismic risk.

This can be seen in several large active fault systems, such as the San Andreas Fault (California), the North Anatolian Fault (Turkey) and the Dead

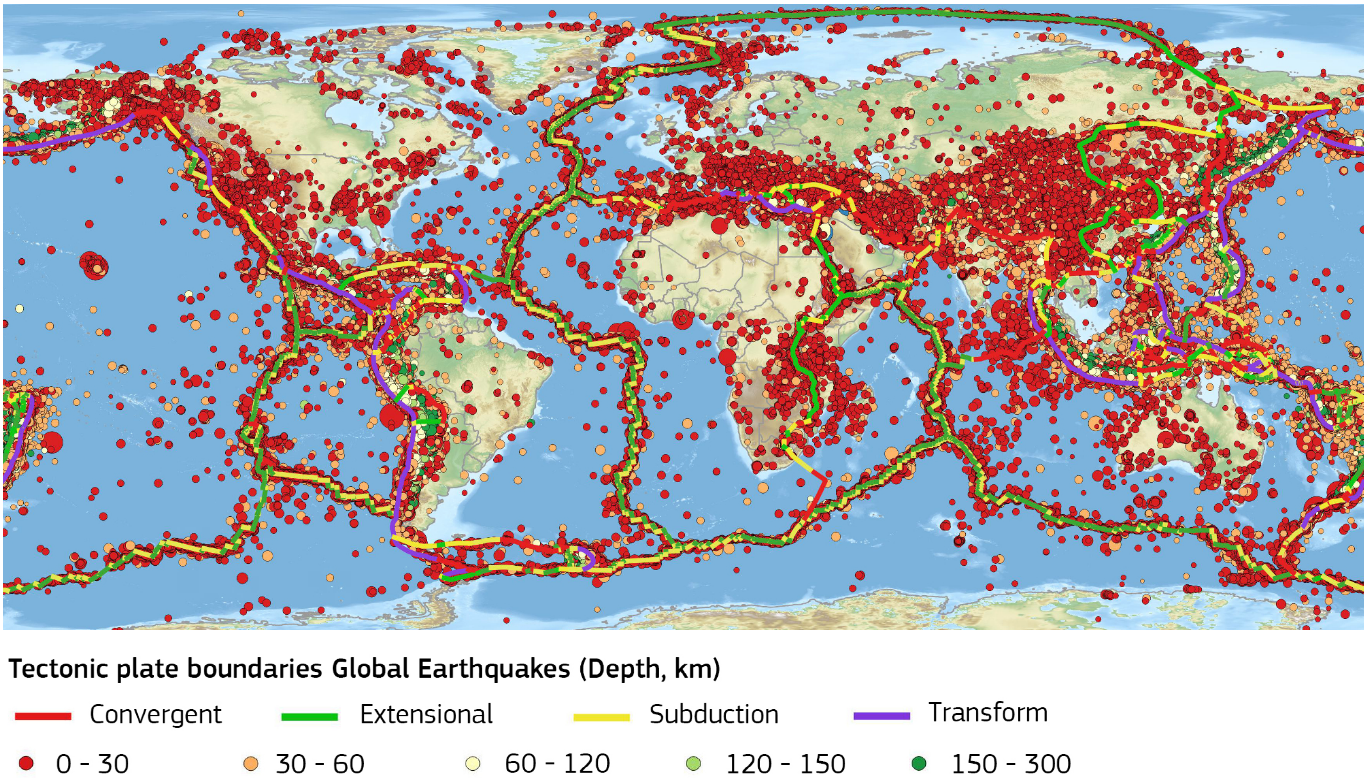
Sea Transform Fault (Israel, Jordan). These active fault systems may extend over many hundreds of kilometres and may experience frequent moderate-to-large earthquakes (M6 to M7.5). Owing to their proximity to many large urban centres, these systems can pose a significant threat to society (e.g. Istanbul). While the vast majority of earthquakes tend to occur in the regions of highest tectonic stress close to plate boundaries, tectonic earthquakes can occur within the lithospheric plates themselves. Intraplate regions are generally characterised by low rates of tectonic deformation, so the recurrence intervals between large events are typically significantly longer (in the order of thousands to tens of thousands of years) than those of plate boundaries. Although large intraplate events are infrequent, they can produce stronger shaking than their plate boundaries counterparts, and this is often felt over a larger area, as in the case of the 1811-12 New Madrid earthquakes in the east of the United States.

3.1.1.2 Past major earthquakes

From the time of the earliest civilisations to the advent of the era of instrumental recording, descriptions of earthquakes can be found in many historical sources. Global archives of historical earthquakes include the United States National Geophysical Data Center (NGDC n.d.) and the Global Historical Earthquake Archive (Albini et al., 2014). A few historically relevant events are described herein. There have been reports of earthquakes in the Mediterranean region, the Middle East, China and Japan since the fifth century BCE. Notable earthquakes in early civilisations include the 464 BCE Sparta (Greece) event and the 227 BCE Dodecanese Islands event, the latter noted for its destruction of the lighthouse statue of the Colossus of Rhodes. As more historical sources survive from mid-

FIGURE 3.1

The global distribution of earthquakes in the period 1900 CE to 2014 CE
Source: Weatherill et al. (2016), Storchak et al. (2015) and global plate boundaries from Bird (2003)



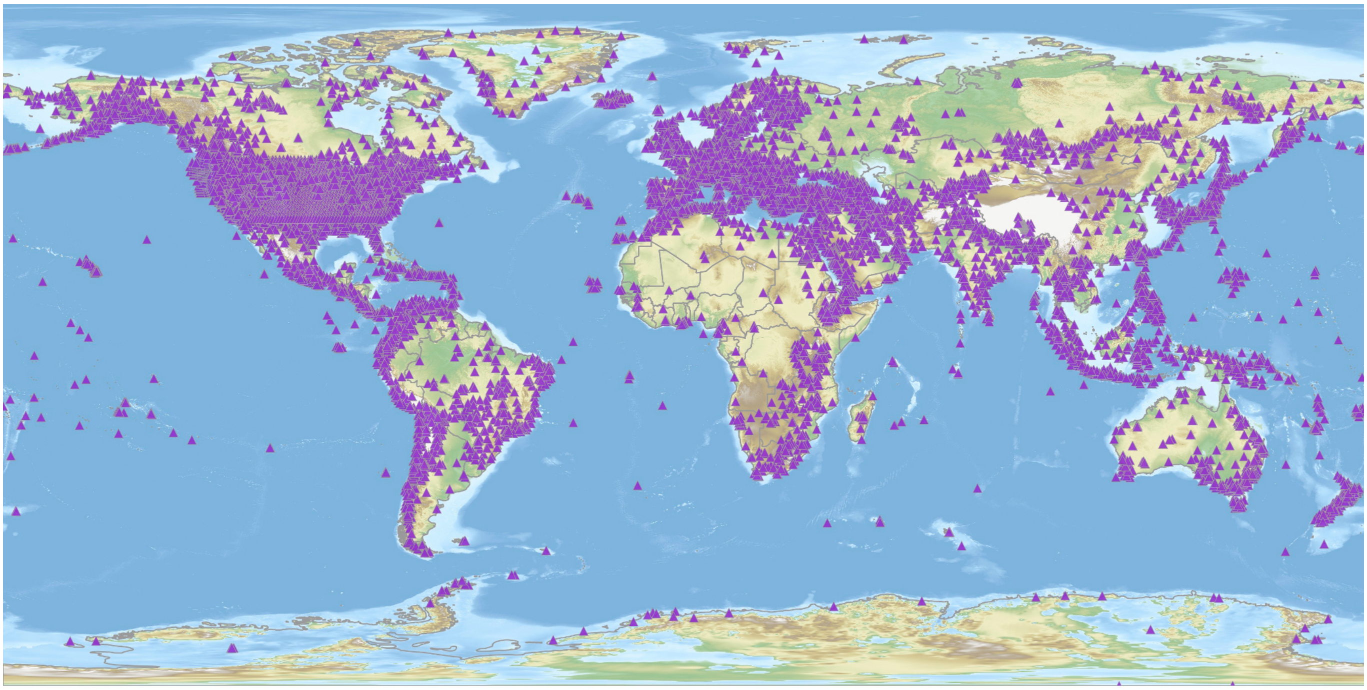
to-late antiquity (300 CE to approximately 750 CE), descriptions of the destruction caused by major events can help to determine the size and location of large earthquakes. Records exist of many catastrophic earthquakes in the Mediterranean and Middle East, including the 365 CE subduction earthquake in Crete, which had an estimated magnitude between M8.0 and M8.3. From 1000 CE to 1500 CE, many major earthquakes occurred in this region, including the 1457 Erzincan earthquake (estimated to have caused 32 000 deaths) and the 1202 Damascus earthquake (estimated to have caused 30000 deaths).

The 16th to 18th centuries saw a considerable expansion of geographical coverage of earthquake records, as settlements were established across the Americas and trade expanded between Europe and Asia. The 1556 Xian (China) earthquake (M≈8) is believed to be the most deadly on record, having caused an estimated 830 000 deaths (Bilham, 2004). During the same period in Europe and the Middle East, two events stand out. The first is the 1509 Istanbul earthquake, which ruptured much of the North Anatolian Fault in the Sea of Marmara, resulting in thousands of deaths. The second is the 1755 Lisbon earthquake (M=8.5 ± 0.3, Martínez Solares and López Arroyo, 2004) and its accompanying tsunami. The devastation to the city of Lisbon, and to many towns along the Atlantic coast of Portugal, Spain and Morocco, contributed to between 60 000 and 100 000 deaths.

The 19th and 20th centuries marked the watershed between the era of historical observation and scientific investigation. Earthquakes such as those of 1906 in San Francisco, USA (M7.8), 1908 in Messina, Italy (M7.2), and 1923 in Kanto, Japan (M7.9), formed the catalyst for innovations in seismic design in these countries. From the second half of the 20th century to the present day, we have witnessed some of the largest earthquakes recorded, including those of 1960 in Valdivia, Chile (M9.4), 2004 in Banda Aceh, Indonesia (M9.1), and 2011 in Tohoku, Japan (M9.0), with

FIGURE 3.2

Seismic recording stations with data contributing to the ISC.
Source: authors



a combined total death toll of more than 300 000 people.

In Europe, the 20th century has seen fewer catastrophic events. Nonetheless, since the 1908 Messina earthquake, Italy has experienced several significant events, such as those of 1915 in Avezzano (M7.0), 1980 in Irpinia (M6.9), 2009 in L'Aquila (M6.3), and 2016 in Norcia (M6.2). The most important events that occurred in Greece include the earthquakes of 1953 in Kephalonia (Ms=7.2), 1978 in Thessaloniki (Ms=6.5), 1986 in Kalamata (Ms=6.0), 1999 in Athens (Ms=5.9) and 2015 in Lefkada (Mw=6.4). Turkey has also been struck by many major events, such as the 1903 Malazgirt (M6.7), 1939 Erzincan (M7.8) and 1999 Izmit and Duzce (M7.6 and M7.2) earthquakes.

3.1.1.3 Monitoring seismic activity

The recording and archiving of seismic events throughout history is fundamental to our understanding of the earthquake process. For much of recorded history, our knowledge of the occurrence and location of earthquakes has come from descriptive records made by contemporary scholars and, in later centuries, from public administrative archives. Quantification of the location and size of earthquakes is made possible, albeit with substantial uncertainty, via the use of macroseismic intensity, a descriptive metric that aims to classify the extent of earthquake damage for many locations using a standard scale. Systematic recording of seismic waves using more precise seismometry began at the end of the 19th century. The modern era of instrumental seismology was transformed, however, in the early 1960s with the establishment of the World-Wide Network of Seismograph Stations, which deployed more than 120 continuously recording stations. The International Seismological Centre (ISC) has maintained the most comprehensive bulletin of parameterised seismic events since 1964. The ISC bulletin defines the location and size of earthquakes from an integrated network of approximately 14 500 seismic stations (see Figure 3.2), with data fed in from various local and regional seismic networks across the globe (Storchak et al., 2015). Today, hundreds of seismic recording networks are in operation worldwide, the vast majority of which contribute to the production of the ISC comprehensive bulletin of seismicity.

3.1.2 Earthquake hazard assessment

3.1.2.1 Seismic hazard assessment methodologies

Characterisation of the effects of earthquakes on the built environment requires several datasets. Regarding hazard assessment, these can include earthquake catalogues (historical and instrumental), active geological faults, geodetic estimates of crustal deformation, seismotectonic features and paleoseismicity. The quality, accuracy and quantity of these input datasets dictate the choice of methodology for seismic hazard assessment. Consequently, seismic hazard may be analysed in two main ways: deterministically, in which a single earthquake scenario is identified, or probabilistically, in which all potential earthquake scenarios are explicitly considered along with their likelihood of occurrence.

Earthquake hazard assessment identifies the likelihood of ground shaking across a region. This is a fundamental component in hazard mapping for design codes and seismic risk assessment.

Deterministic approaches may be perceived as conceptually simpler and more conservative. The probabilistic approach requires complex mathematical formulations to account for uncertainties in earthquake size, location and time of occurrence, and the outputs relate various levels of ground shaking that may be observed at a site to their corresponding exceedance probabilities in a given time period. This relationship between ground shaking and probability constitutes a hazard curve. The expected ground shaking for a pre-established probability of exceedance within a time span (e.g. 10 % in 50 years) or a return period (e.g. 475 years) can be calculated for a given region, thus enabling the production of a hazard map.

These maps are used to define the seismic action in design codes, such as the Eurocode 8 (CEN, 2005). By adopting a methodology in which uncertainties are explicitly incorporated into the process, the probabilistic approach avoids the potential subjectivity associated with the identification of adverse scenarios, and provides a more objective formulation of the likelihood of ground shaking. For critical infrastructures such as nuclear facilities, the probabilistic approach is now the standard practice (Renault, 2014).

In recent decades, Probabilistic Seismic Hazard Analysis (PSHA) has reached an evident level of maturity (e.g. Petersen et al., 2015; Woessner et al., 2015). Since its inception by Cornell (1968) and McGuire (1976), several crucial developments in PSHA can be identified, such as the complex representation of seismic sources, the derivation of new models to describe the recurrence of earthquakes and sophisticated equations to predict the resulting ground motion. These developments have occurred against the backdrop of continued improvements in modelling software to allow for complex calculations. The flexibility of the probabilistic framework has contributed to the credibility of the method and acceptance by engineers, planners and regulatory bodies.

The quality of the input datasets guides the choice of the methodology for the development of the PSHA model (Giardini, 1999). In this context, three main approaches can be identified:

- historical — defining statistical seismogenic sources to describe the historical record of seismicity (location in space and time, magnitude frequency distribution of large earthquakes);
- time-independent — incorporating geological and geodetic evidence with both instrumental and historical earthquake catalogues to derive a seismogenic model covering earthquake cycles up to thousands of years; and
- time-dependent — which accounts for periodic trends in earthquake recurrence to predict the likelihood of earthquakes occurring in a source given the time elapsed since the previous event.

The historical approach is informed exclusively by the observed earthquake record, the duration of which is often insufficient to evaluate the complex phenomena of earthquake cycle. Conversely, time-dependent models require a detailed paleoseismological history of a seismogenic source. In most regions of the world such information is not yet available, and, therefore, the application of time-dependent seismic hazard analysis is still limited to only a few regions (e.g. California, Japan). Among the many outputs of PSHA, it is possible to identify the predominant seismic source contributing to the seismic hazard at a site in terms of its spatial and magnitude properties, in a process known as disaggregation (Bazzurro and Cornel, 1999). This information can be used to select events for deterministic analysis (scenarios) or selection of ground motion records.

Various software packages, both open and proprietary, are available for the calculation of seismic hazard using deterministic or probabilistic approaches. OpenQuake (Pagani et al., 2014) is one such package and was used in recent regional projects for seismic hazard assessment in Europe, the Middle East, South and Central America, Caribbean and Africa.

3.1.2.2 Sources of uncertainties in hazard assessment

Seismic hazard assessment is characterised by a large spectrum of uncertainties, generally categorised as epistemic and aleatory. The epistemic uncertainty leads to multiple hazard curves, while the aleatory variability controls the shape of the hazard curves (Bommer and Abrahamson, 2006).

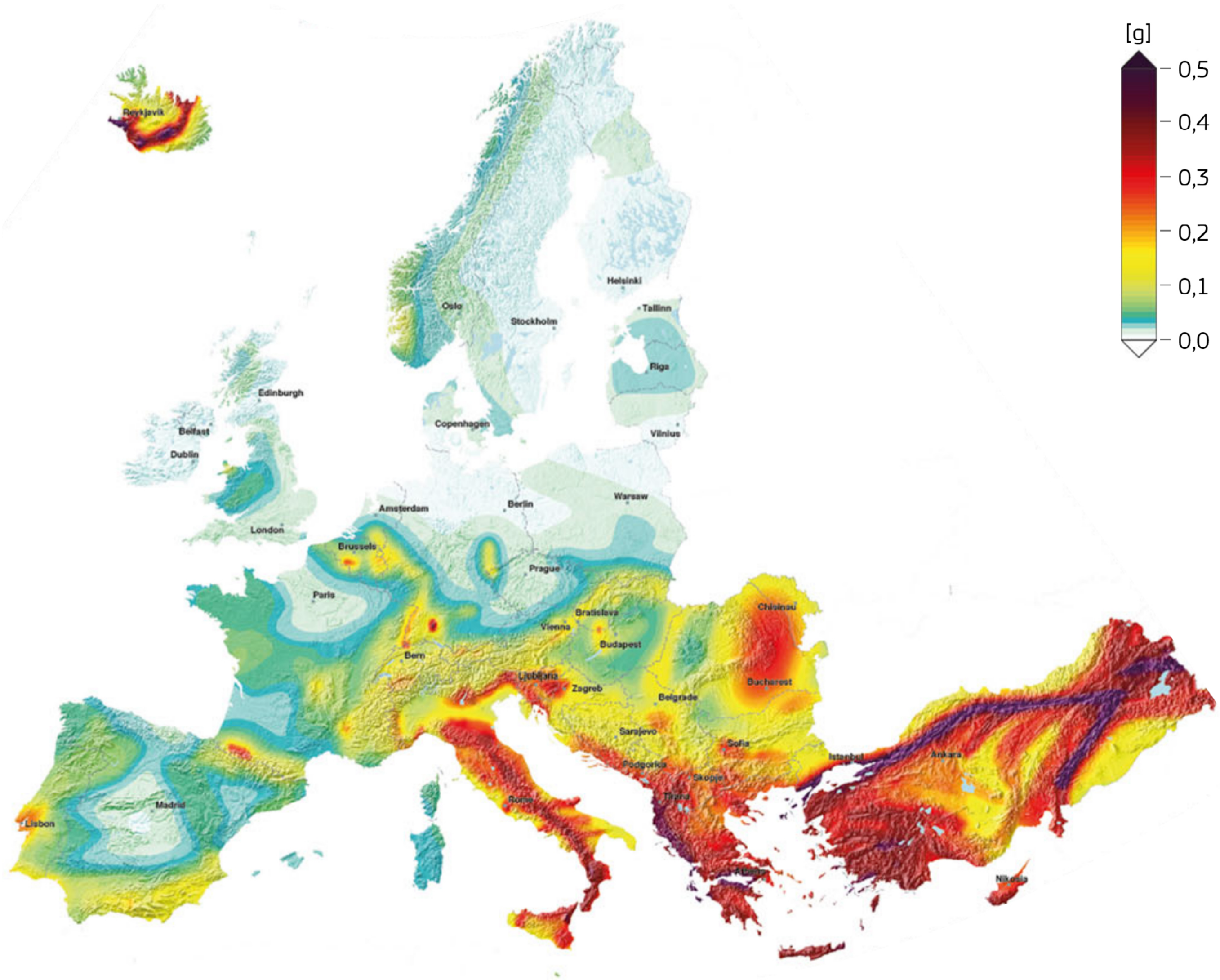
Sources of epistemic uncertainty may take the form of alternative models, both for the seismogenic source and/or ground motion, or may describe the uncertainty in the parameterisation of specific models. Concerning the seismogenic source, alternative models may describe different geometric configurations of the source, different models of magnitude recurrence or alternative models to relate the magnitude of the earthquake to the dimensions of the rupture. Ground Motion Prediction Equations (GMPEs) describe the expected ground motion at a site, given the size and characteristics of the earthquake source, site-to-source distance and the local geological conditions. Given the wide variety of GMPEs, selecting all those that are appropriate for modelling the intrinsic epistemic uncertainty can be challenging (Bommer et al., 2010; Cotton et al., 2006; Danciu et al., 2016; Kale and Akkar, 2013; Scherbaum et al., 2009). For Europe, a set of GMPEs has been suggested based on several studies (Delavaud et al., 2012; Zafarani and Mousavi, 2014;

Kale et al., 2015).

The concept of aleatory uncertainty in PSHA is intended to represent those elements of the earthquake process that may be considered irreducibly random, for which the specific value can be described only in terms of a probability distribution. For example, the magnitude and location of a future rupture cannot be predicted with absolute certainty, but the probability of future rupture magnitude and locations can be estimated. Consequently, these parameters are considered to be aleatory uncertainties, the probability distributions of which are explicitly accounted for in the process of calculating the hazard curve. In addition to these uncertainties, the variability in the ground motion models is a dominant factor in seismic hazard estimates. GMPEs also quantify the variability of the ground motion given the source, path and site conditions, and various studies (e.g. Strasser et al. 2009, Douglas 2010) have recognised

FIGURE 3.3

Reference seismic hazard map depicting peak ground acceleration levels for a 10 % probability of exceedance in 50 years for a reference rock condition of Eurocode 8 Type A.
Source: adapted from Woessner et al. (2015)



that neglecting the ground motion variability leads to an underestimation of the hazard.

3.1.2.3 Seismic hazard in Europe

The 2013 European Seismic Hazard Model (Woessner et al., 2015) is the latest seismic hazard model to be fully harmonised across the Euro-Mediterranean region. This model was developed within the SHARE (Seismic Hazard Harmonization in Europe — SHARE, n.d.) project funded by the European Union's 7th Framework Programme (FP7) for Research and Innovation. SHARE provides a significant improvement compared with previous efforts, mainly as a result of a number of factors:

- the new European historical and instrumental earthquake catalogue (SHEEC, n.d.);
- the homogeneous database of the fully parameterised seismic faults (more than 68 000 km of mapped faults) (Basili et al., 2013);
- the new regional reference geodetic mapping;
- the creation of a generic model for maximum magnitude for the entire region;
- the characterisation of uncertainties associated with ground motion (Delavaud et al., 2012);
- the consideration of multiple methods to forecast earthquake activity;
- the development of three independent seismogenic models depicting the expected recurrence of earthquakes; and
- the consideration of epistemic uncertainties for model components and hazard results.

The OpenQuake engine was used to perform the hazard calculations, the input models and main results of which can be found in the European Facility for Earthquake Hazard and Risk (EFEHR, n.d.). Moreover, SHARE promoted discussions with representatives of Sub-Committee 8 (SC8 — CEN, 2005) of the European Committee for Standardization (CEN) Technical Committee 250 (CEN/TC250) 'Structural Eurocodes', in order to ensure the compatibility of the hazard output specifications with the Eurocode 8 engineering requirements. Additional SHARE achievements include a critical overview of regulations from seismically active countries (i.e. Italy, United States, New Zealand, Japan and Canada), the use of seismic risk assessment in the calibration of seismic design actions in codes (Silva et al., 2015) and the minimum capacity of buildings designed without seismic actions to evaluate the minimum hazard level below which seismic zonation is not necessary.

Figure 3 illustrates the reference seismic hazard map in terms of peak ground acceleration for a 10 % probability of exceedance in 50 years for a reference rock condition of Eurocode 8 Type A ($v_{s,30}$ = 800 m/s).

3.1.3 Exposure and vulnerability

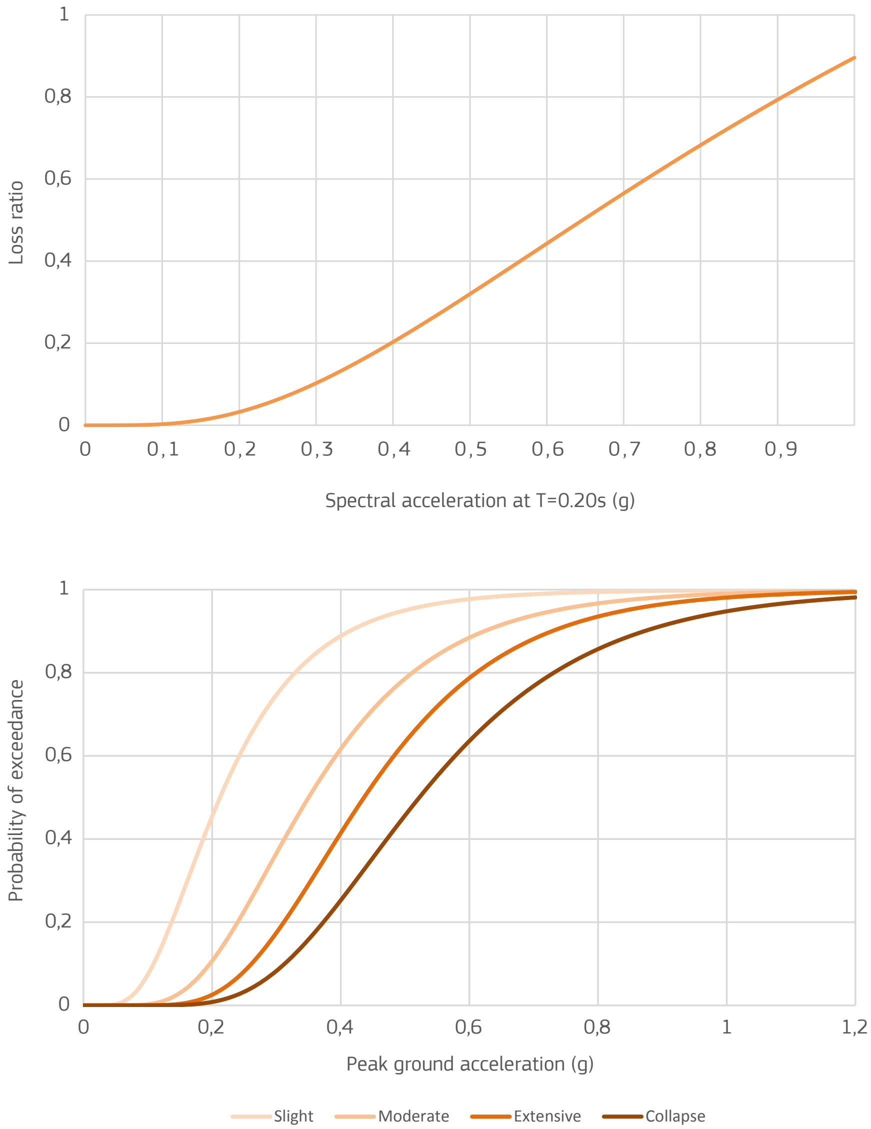
3.1.3.1 Characterization of the built-up environment and population

The development of an exposure model capable of providing information about the location, value and vulnerability classification of the elements exposed to earthquakes depends highly on the intended scale of the risk analysis. For a local assessment, a building-by-building data collection campaign can be organised, in which mobile devices are used to geo-reference and classify assets according to their structural attributes. Recently, the Global Earthquake Model (GEM) has released an Android application (Inventory Data Capture Tool) capable of performing such a task, using a building taxonomy (Brzev et al., 2013). At a larger scale, satellite remote sensing and in situ omnidirectional imaging represent innovative and efficient procedure to rapidly characterise the built environment (Wieland et al., 2012). For large-scale exposure modelling (e.g. regional or national), the use of building census surveys and socioeconomic data might be preferable.

These datasets contain information about the number of buildings or dwellings, usually classified according to a set of attributes relevant for defining vulnerability (e.g. construction material, number of storeys, age of construction). A mapping scheme is often developed in order to establish the link between the information contained in a census survey and a set of vulnerability classes (e.g. Erdik et al., 2003a; Crowley et al., 2009; Silva et al., 2014a). The result is usually a residential exposure model at the smallest administrative level with the distribution of the number of buildings across a set of vulnerability classes, associated replacement cost and number of occupants. For industrial and commercial buildings, similar datasets are usually not available. Instead, socioeconomic data such as number of workers in the different sectors (e.g. manufacturing, mining, retail) can be utilised to estimate an approximate built-up area and replacement cost. Within the FP7 European project on the network of European research infrastructures for earthquake risk assessment and mitigation (NERA) (Crowley et al., 2012), building data from all of the European countries were collected and used to calculate the fraction of each building class at the first administrative level. These results were input into the exposure database of GEM to derive exposure datasets at the national level. Satellite imagery and volunteered geographical information (VGI) are rapidly changing the manner in which exposure modelling is performed. High-resolution datasets (e.g. Global Human Settlements Layer (Pesaresi et al., 2016)) now have sufficient temporal and spatial depth to delineate built-up areas. This information can be used to improve the spatial resolution of existing datasets, or to develop new ones based on the observed building footprints. This approach is usually combined with data collected in the field in order to understand the most common types of construction for each area. VGI can also contribute significantly to the improvement or development of exposure datasets. For example, OpenStreetMap contains critical information for large urban centres such as Berlin, Tokyo, Kathmandu or Jakarta. A description of various exposure modelling techniques can also be found in Pittore et al. (2016).

FIGURE 3.4

Vulnerability (above) and fragility (below) functions. Source: adapted from Yepes et al. (2016)



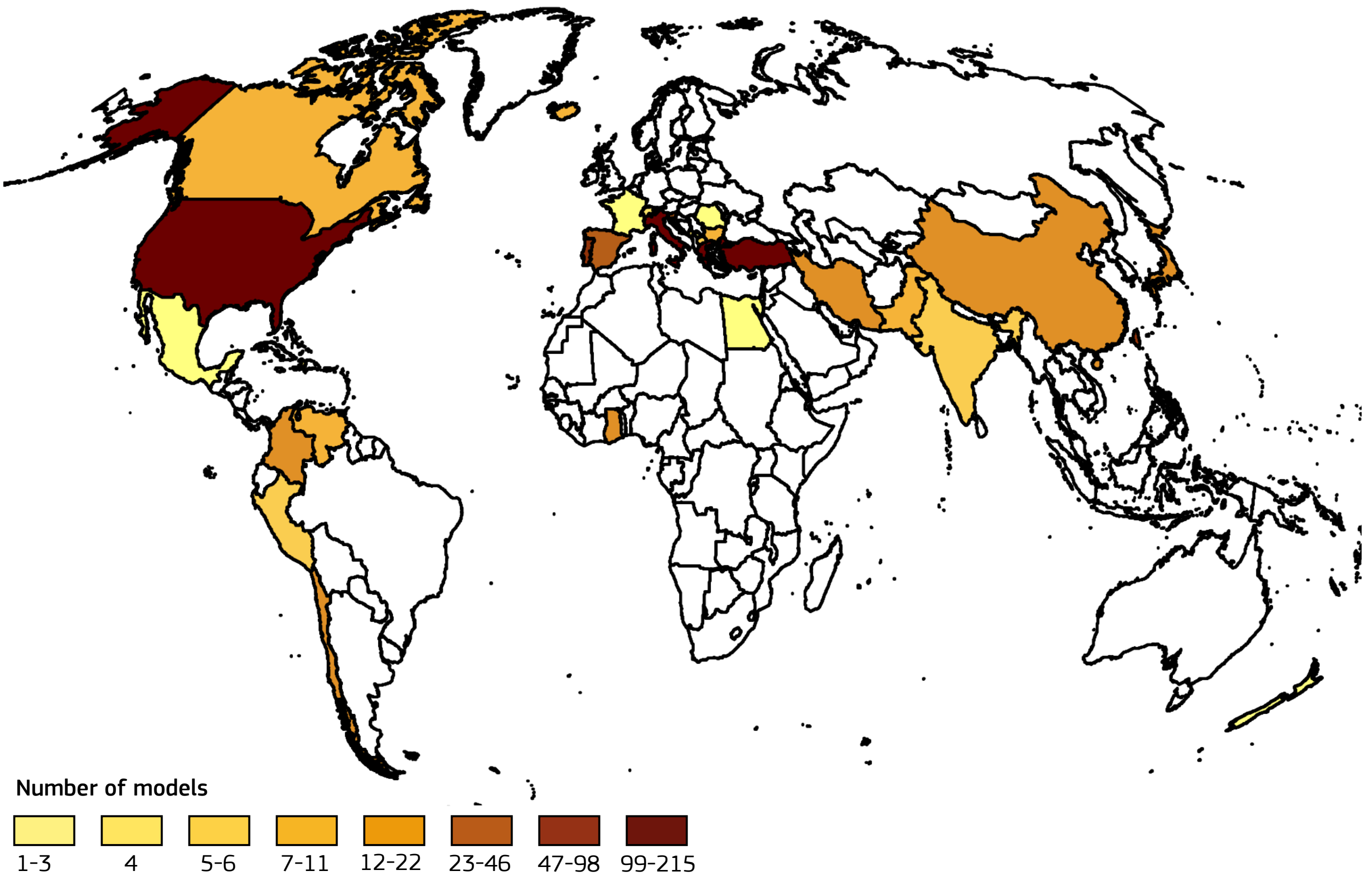
3.1.3.2 Vulnerability assessment methodologies

Vulnerability is defined as the susceptibility of assets (e.g. people, buildings, infrastructure) exposed to earthquake hazards to incur losses (e.g. deaths, downtime and economic loss). Vulnerability functions (see Figure 3.4) can be derived 'directly' from regression on historical loss data (empirical), through the elicitation of expert opinion (heuristic), or by using numerical simulations (analytical). Vulnerability functions can also be derived 'indirectly' from the combination of a fragility function and a damage-to-loss model. A fragility function (see Figure 3.4) describes the propensity of assets (e.g. buildings) to sustain damage under earthquake effects and can be developed empirically, heuristically or analytically (i.e. where a numerical model simulates the response of a structure under increasing hazard intensities) or through a combination of such approaches (hybrid). A damage-to-loss model instead relates values of loss to thresholds of damage. Approaches for mathematically deriving indirect vulnerability functions from fragility functions and loss models are explained in detail in Rossetto et al. (2014a).

Empirical approaches to earthquake vulnerability and fragility function definition are extensively used in the insurance industry, and the academic literature in this field has been rapidly increasing over the past four decades (Ioannou and Rossetto, 2015). A number of sources for post-earthquake damage or loss data are available (e.g. surveys commissioned by authorities in order to assess structural safety or to evaluate the cost of repair for insurance, tax reductions or government aid distribution purposes), and the reliability of empirical relationships is heavily dependent on the quality and size of the adopted observational databases. Owing to the nature of empirical data, vulnerability and fragility functions that are based on severely biased datasets and mainly on aggregated data can be found in the literature (Rossetto et al., 2015). A rating system for comparing the reliability of different empirical fragility functions is presented in Rossetto et al. (2014b). In addition, GEM has recently published a set of guidelines (Rossetto et al., 2014a) for the con-

FIGURE 3.5

Global vulnerability model coverage in the GEM vulnerability database.
Source: Yepes et al. (2016)



struction of empirical functions from single or multiple earthquake event databases.

Heuristic fragility and vulnerability functions have been derived either where there was limited information regarding past earthquakes or where the asset was difficult to model numerically (ATC 13, 1985; Jaiswal et al., 2012).

Characterisation of assets and population in a region and their susceptibility to suffer damages or losses is one of the key elements by which to understand risk.

An abundance of analytical fragility functions exists, which are predominantly derived for buildings and bridges. A variety of analysis methods and structural models with different levels of complexity (e.g. Martins et al., 2016; Akkar et al., 2005) have been used to construct such fragility functions. The adequacy of the adopted approach to represent the fragility of the structure depends on the structure's expected behaviour under ground shaking. A rating system for comparing the reliability of different analytical fragility functions is presented in Rossetto et al. (2014b) and guidelines for the construction of analytical vulnerability and fragility functions for low- to mid-rise buildings can be found in D'Ayala et al. (2014) and for tall buildings in Porter et al. (2014).

It is clear that each approach to the construction of fragility and vulnerability functions (i.e. empirical, analytical, heuristic and hybrid) has its advantages and disadvantages. However, in each case, for the function to be credible and useable, it is essential that the sources of uncertainty are identified and that the uncertainty associated with the functions is quantified. This is not common, and major sources of uncertainty are commonly ignored (e.g. record-to-record variability, uncertainty in the damage criteria, building-to-building variability).

3.1.3.3 Existing exposure and vulnerability databases

Despite the usefulness of exposure information, the availability of open databases of exposure is quite limited. GEM released an exposure database in 2014 (Gamba, 2014) with building information on a global scale, but with different levels of detail depending on the country. The number of buildings and dwellings was mostly calculated using population data (GRUMP, CIESIN, 2004), and national or subnational mapping schemes. For Europe, these mapping schemes were developed using the results from the European project NERA. It is also worth mentioning the exposure database proposed by the United States Geological Survey (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) group, which also comprises worldwide information at the national scale (Jaiswal et al., 2010).

With regard to vulnerability databases, recently, several institutions have collected fragility and vulnerability functions from the literature. The most notable examples are the GEM database of vulnerability and fragility functions for buildings, described in Yepes et al. (2016), and the FP7 European project SYNER-G database for infrastructure fragility (Crowley et al., 2014; Pitilakis et al., 2014). Figure 3.5 illustrates the global coverage of earthquake vulnerability functions in the GEM database. It highlights a lack of vulnerability functions for many developing countries at risk. Moreover, all these databases indicate a predominance of fragility over vulnerability functions and damage-to-loss models. The paucity of vulnerability functions for developing countries can be attributed to a lack of past event loss data to build or calibrate the vulnerability models, and the difficulty associated with modelling non-engineered buildings. Apart from vulnerability functions, a number of indices exist that provide relative measures of vulnerability across geographical areas and that incorporate socioeconomic measures. Forms of such empirical vulnerability indices are used in the Global Assessment Reports (supported by the Global Risk Data Platform of UNEP/GRID-Geneva) and by the USGS's PAGER group.

3.1.4 Seismic risk assessment, loss estimation and risk mitigation

3.1.4.1 Early warning systems and near-real time loss assessment

Emergency rescue reports from several past earthquakes indicate that more than 90 % of successful rescues occur within the first 24-48 hours (Oliveira et al., 2006). Successful rescues depend greatly on the preparedness of the local authorities and the efficient allocation of limited resources shortly after seismic events. For this reason, a number of systems have been developed in the last decades either to trigger early warnings or to rapidly assess the expected damages. EWS (Zollo et al., 2009; Alcik et al., 2009, Hoshiba et al., 2008) aim to launch alerts seconds before the arrival of the destructive seismic waves, usually through the interpretation of the amplitude of P waves. This lead-time may be useful to initiate emergency measures, such as the controlled shutdown of gas pipelines and critical facilities and speed reduction of rapid-transit vehicles, and to advise the population to follow the necessary precautions (Wu and Kanamori, 2008). Several European projects have investigated the effectiveness of such systems for the European territory (SAFER, n.d.; REAKT, n.d.), but currently a large-scale operational system does not exist.

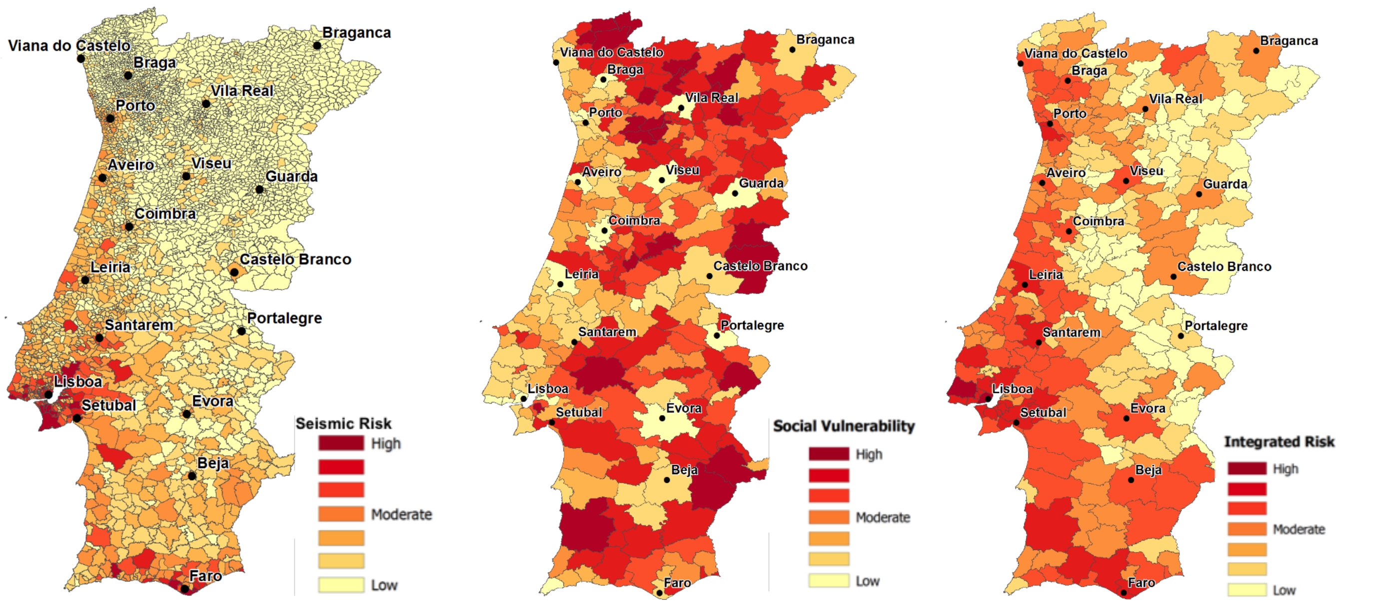
Near-real time loss assessment systems focus on the estimation of the expected damage using existing exposure and vulnerability models, and ground shaking computed shortly after the seismic event. The USGS PAGER group has developed one of the best-known systems, which provides first-order estimates of human and economic losses at a global scale (Wald et al., 2012). At the national level in Europe, a few systems have also been developed for Italy, Bulgaria, Romania, Portugal and Turkey (e.g. Erduran et al., 2012; Erdik et al., 2003b). The ongoing pilot project ARISTOTLE (n.d.), funded by EU budget, will provide scientific support to European Emergency Response Coordination Centre (ERCC) in the period 2016-17, not only for earthquakes, but also for other hazards such as tsunamis, volcanic activity and meteorological hazards.

3.1.4.2 Evaluation of earthquake scenarios

The assessment of earthquake scenarios can play a critical role in the development of risk-reduction measures. These may include the creation of emergency plans, the development of

FIGURE 3.6

Seismic risk (left), social vulnerability (centre) and integrated risk (right) for Portugal
Source: adapted from Burton and Silva (2015)



infrastructure to support the affected regions or the organisation of earthquake risk awareness campaigns. For example, Anhorn and Khazai (2014) investigated the suitability of shelter spaces in the Metropolitan Area of Kathmandu (Nepal), considering a set of potential destructive earthquakes. Likewise, Mendes-Victor et al. (1994) and ERSTA (2010) estimated the expected economic and human losses for high-magnitude events in the city of Lisbon and the Algarve region, respectively. These results were used by the Portuguese Civil Protection authorities to elaborate seismic risk emergency plans. Scenario events may be based on past historical earthquakes (e.g. Bendimerad, 2001) or may be defined through the investigation of seismogenic sources around the region of interest (e.g. Ansal et al., 2009). The distribution of ground shaking at the location of the collection of assets is used with fragility or vulnerability functions to assess damage or losses, respectively. Several software packages can be used for the assessment of earthquake scenarios such as Earthquake Loss Estimation Routine (ELER) (Hancilar et al., 2010), OpenQuake (Silva et al., 2014b) or SEismic Loss EstimatioN using a logic tree Approach (SELENA) (Molina et al., 2010).

Several past European initiatives have covered the development of earthquake scenarios for large urban centres. The RISK-EU (2001-4; Mouroux and Le Brun, 2006) and LESSLOSS (2004-7; Calvi and Pinho, 2004) projects explored the impact of several seismic events in urban centres such as Bucharest, Catania, Nice, Lisbon, Istanbul, Sofia and Thessaloniki. More recently, the European project STREST (Harmonized approach to stress tests for critical infrastructures against natural hazards) (STREST, n.d.) explored the impact of specific seismic events in critical facilities, such as industrial structures in Central Italy.

Hazard, exposure and vulnerability are the key elements for seismic risk assessment to estimate the consequences of earthquakes and the potential for human and economic losses, which can support decision-makers in the development of risk-reduction strategies.

These projects featured the involvement of several stakeholders to ensure that the final results would be useful for disaster risk management (DRM).

3.1.4.3 Probabilistic seismic risk assessment

The assessment of probabilistic earthquake losses can be performed through two main approaches: classic PSHA-based risk or probabilistic event-based risk analyses (Cornell, 1968; McGuire, 2004; Silva, 2016). These methodologies have been featured in software packages such as CAPRA (ERN-AL, 2009), OpenQuake (Silva et al., 2014b), SELENA (Molina et al., 2010) or HAZUS (FEMA, 2003).

An example of a probabilistic earthquake loss assessment is presented in Figure 3.6 for Portugal (first panel). In this study, average annual losses at the county level were calculated using a time-independent PSHA model (Silva et al., 2014a). This information can inform local governments, civil protection authorities and other stakeholders in the development of risk-reduction measures. These can include the improvement and/or enforcement of seismic codes (e.g. Spence, 2004), the development of retrofitting campaigns (e.g. Erdik and Durukal, 2008), the improvement of urban planning (Sengezer and Koç, 2005), the development of financial mechanisms to transfer the risk from the public sector to the international reinsurance market (e.g. Bommer et al., 2002), or the strategic allocation of funds for risk reduction and prevention. For example, in 2009, the Italian Government invested almost EUR 1 billion in a seismic prevention programme at the national scale, led by the Civil Protection Department. In order to understand how to distribute the funds across the different regions in Italy, a seismic risk assessment study was conducted and the funds were distributed proportionally to the earthquake risk (Dolce, 2012). An effort to assess quantitatively earthquake risk in Greece in terms of economic impact was developed by Papadopoulos and Arvanitides (1996).

Despite the usefulness of such metrics, they neglect local socioeconomic conditions. For this reason, several social scientists (e.g. Carreño et al., 2007; Khazai and Bendimerad, 2011) have explored the concept of integrated or holistic risk. This approach aims to aggravate or attenuate the direct risk (e.g. average annual losses) according to a social vulnerability index. This index is derived considering a large number of socioeconomic indicators such as crime, education, poverty, age or unemployment. The distribution of socioeconomic vulnerability and integrated risk for Portugal is presented in Figure 3.6 (Burton and Silva, 2015).

These results reflect the earthquake resilience of different regions within the same country, and, thus, where a longer recovery time should be expected in the event of a disaster. Within the Horizon 2020 (H2020) framework, the SERA project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe) will cover the probabilistic earthquake loss assessment for all European countries.

It is also important to understand that modern societies strongly rely on inter-related systems (building stock, power, water supply, transportation), and that a natural catastrophe might initiate a cascading effect, whereby one disaster triggers another. These effects have been explored in the two European projects Syner-G and STREST.

3.1.5 Conclusions and key messages

In the last decades, earthquakes have been responsible for approximately one-fifth of global annual economic losses, and for a death toll of more than 25 000 people per year. This can have a serious impact on sustainable development, the creation of jobs and the availability of funds for poverty reduction initiatives. This chapter has described several recent developments across the different disciplines of earthquake risk assessment and has highlighted a multitude of resources currently available to the disaster risk-reduction community. The key messages from this chapter are summarised below.

Partnership

The assessment of the impact of earthquakes incorporates many scientific fields, such as seismology, earthquake engineering and social sciences. Neglecting any of these fields will inevitably reduce the accuracy, reliability and usefulness of the resulting risk metrics. The process of risk identification should involve stakeholders from the public and private sectors, and should support ongoing national and international initiatives with the mandate to calculate, communicate and reduce earthquake risk.

Knowledge

In the past two decades, the European Union has funded a large number of projects that have significantly advanced the science of earthquake hazard, vulnerability and risk modelling. Other national and international programmes have also produced datasets, models and tools that are fundamental for the assessment of earthquake risk. Leveraging on this wealth of resources will reduce the replication of efforts. It is important to investigate efficient approaches to the application of existing earthquake risk knowledge into DRM, as described in the preceding section.

Innovation

Earthquake risk assessment has reached a considerable level of maturity, which requires complex software packages (e.g. ELER, HAZUS, OpenQuake, CAPRA or SELENA). It is fundamental to incorporate the wide spectrum of uncertainties from the different risk components (exposure, vulnerability, hazard). Satellite imagery and VGI are enabling the characterisation of the built environment with unprecedented temporal and spatial detail. Moreover, the development of risk-reduction strategies should not only rely on the direct (or physical) impact, but should also incorporate socioeconomic aspects, thus considering the capability of the society to recover from destructive events.

3.2 Geophysical risk: volcanic activity

***Sue Loughlin**, Sara Barsotti, Costanza Bonadonna, Eliza Calder*

3.2.1 Volcanoes and volcanic activity

Volcanoes provide spectacular evidence of the dynamic nature of planet Earth and bring many long-term benefits to society, including rich soils, tourism and geothermal energy. Some erupt frequently and others may appear benign for generations, which means the risk they pose may be underestimated. Understanding the risk first requires characterisation of the volcano and knowledge of the type, magnitude and frequency of past eruptions.

3.2.1.1 Global distribution of volcanoes and volcanoes in Europe

There are about 1 550 known terrestrial volcanoes that have erupted in the past ≈10 000 years and are therefore likely to erupt again in the future; they are described as 'active' (Siebert et al., 2010; Cottrell, 2014).

Volcanic eruptions may cause local to global impacts; in order to understand and mitigate risks, the first step is to recognise a volcano as active and to characterise its past activity.

Most have formed along colliding or diverging tectonic plate boundaries (e.g. the Pacific margins, the Mediterranean, the Lesser Antilles and Iceland; Figure 3.7) and these account for >94 % of known historical eruptions (Siebert et al., 2015); the remainder have formed above mantle 'hotspots' (e.g. Hawaii).

In Europe, volcanism from Spain (Bartolini et al., 2015) to Armenia (Savov et al., 2016) is mainly caused by the convergence of the northward-moving African and Arabian lithospheric plates with the Eurasian plate and microplates in the Aegean Sea and Anatolia (Figure 3.8). In Iceland, volcanism is caused by a combination of rifting at the Mid-Atlantic Ridge and a 'hotspot'. There are 32 volcanoes in Iceland (Ilyinskaya et al., 2015), 47 known volcanoes in continental Europe (Siebert et al., 2010), and many more in autonomous regions, European dependencies and territories in the Atlantic (Canary Islands, Azores, Cabo Verde, Tristan da Cunha, Ascension Island), the Lesser Antilles (Montserrat, Guadeloupe, Martinique, Saba) and the Indian Ocean (La Réunion). About 15 million people in Europe live within just 30 km of an active volcano; of these, more than 2.2 million live within 20 km of the Campi Flegrei caldera in Italy and more than 675 000 live within 10 km of Vesuvius (Siebert et al., 2010).

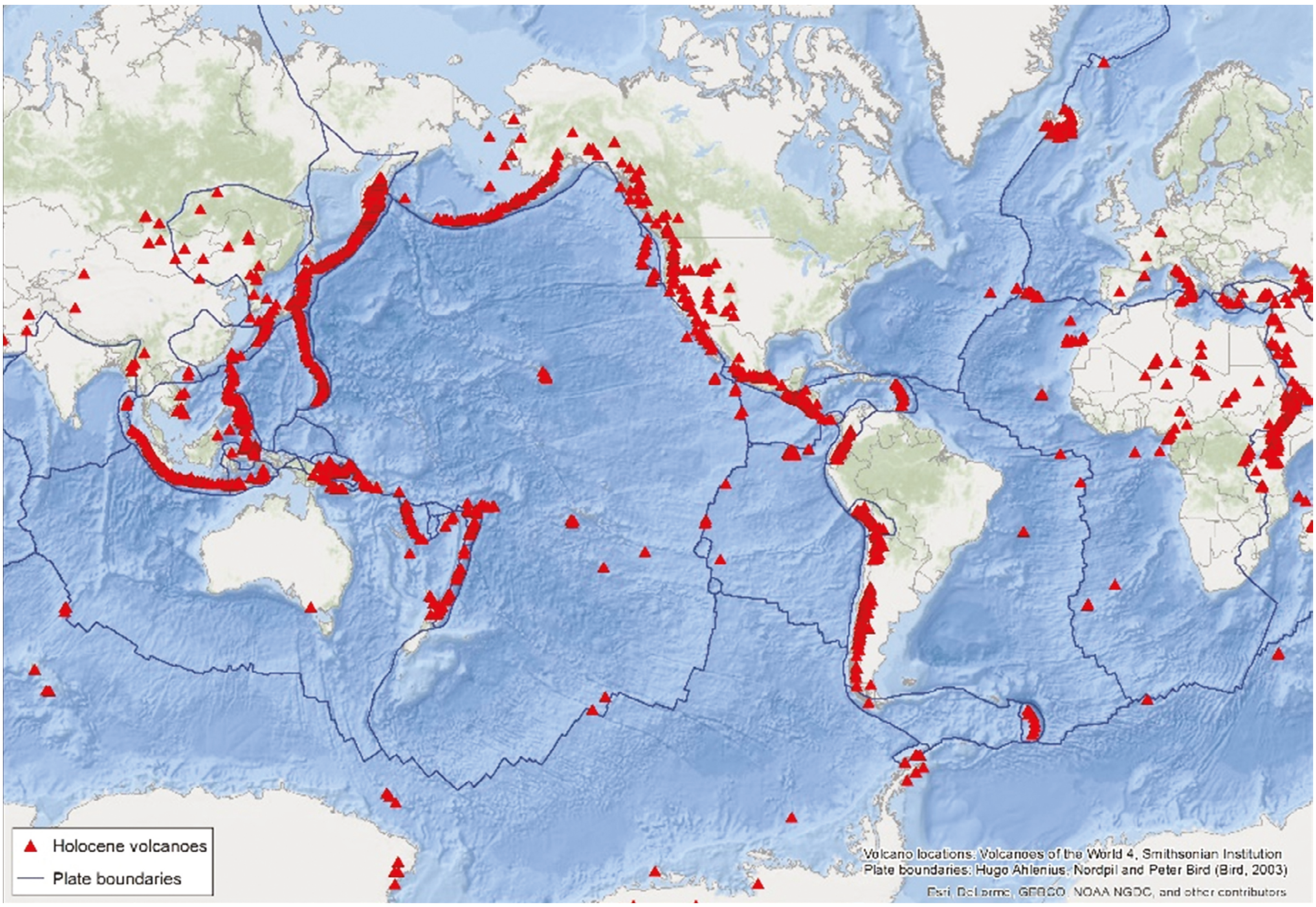
3.2.1.2 Eruption type, duration, frequency and size

Globally, about 70 volcanoes erupt each year and at any one time at least 20 are erupting (Siebert et al., 2010, 2015). Eruptions are complex time-dependent events, which often exhibit distinct phases including effusive (e.g. lava flows/domes) and/or explosive types of activity (e.g. Gudmundsson et al., 2012) over durations of hours to decades (Brown et al., 2015).

Major controls on eruption type include magma chemistry, rheology and volatile content. Eruptions can be measured using magnitude (erupted mass), but volume is often used as a proxy for magnitude for explosive eruptions (e.g. the Volcanic Explosivity Index, see Newhall and Self 1982, Pyle 2015).
Some volcanoes erupt frequently (e.g. Stromboli and Etna), whereas others (e.g. Campi Flegrei) erupt infrequently, with hundreds of years between eruptions (e.g. Selva et al., 2012; Brown et al., 2014). Global data show a power law relationship between magnitude and frequency, such that larger magnitude eruptions are less frequent (Deligne et al., 2010). In order to understand the distribution of eruption types and magnitudes in time and space at a given volcano (and, therefore, the likelihood and type of future

FIGURE 3.7

The locations of known Holocene (past ≈ 10.000 years) terrestrial volcanoes of the world, most of which form near tectonic plate boundaries (Bird, 2003).
Source: Smithsonian Institution (2013)



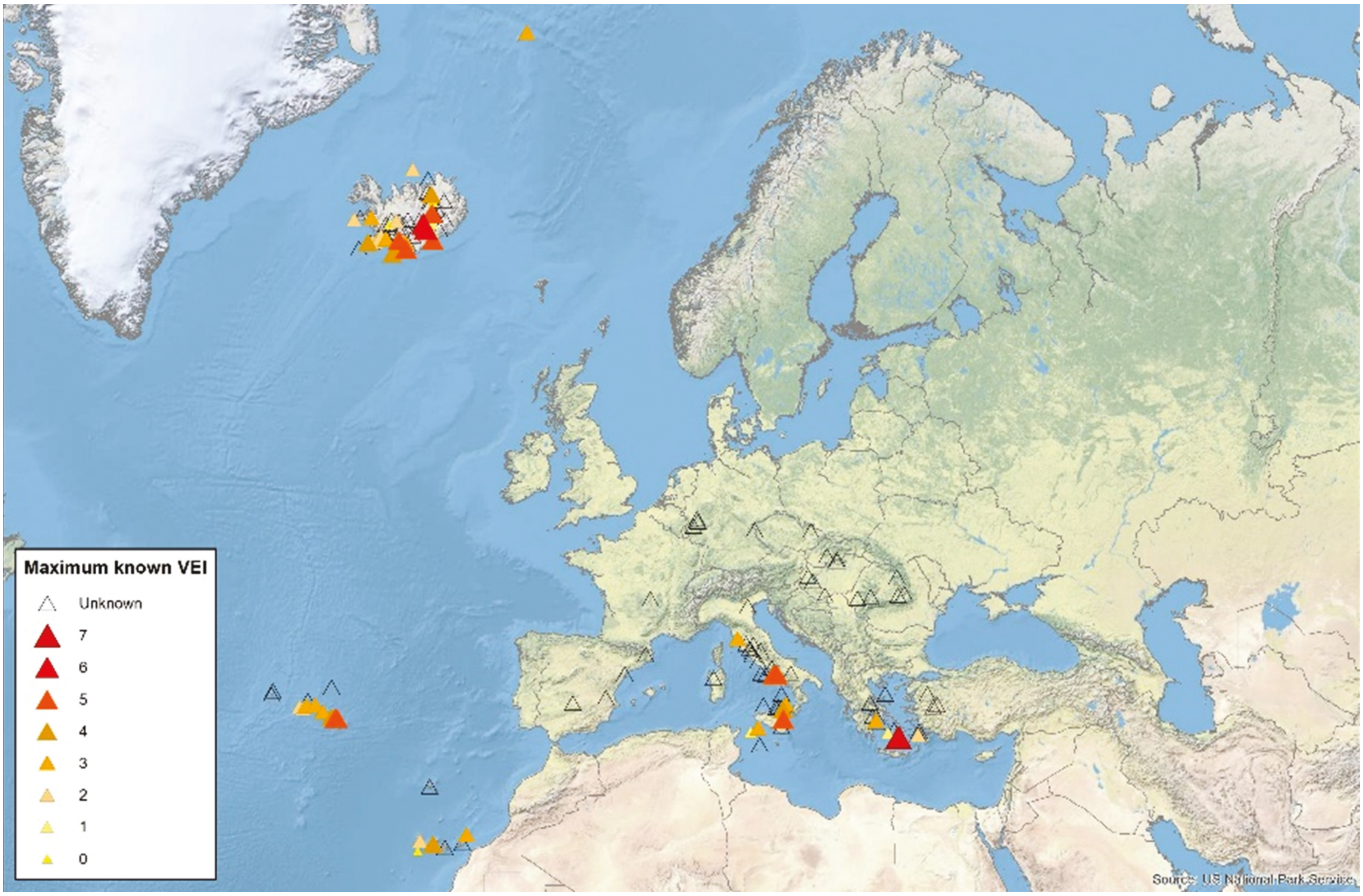
eruptions), geological and geochronological studies are an essential starting point (e.g. Druitt et al., 1999; Orsi et al., 2004; Thordarson and Larsen, 2007; Hicks et al., 2012).

3.2.1.3 Causes of volcanic unrest and eruptions

Eruptions are caused by complex processes including magma overpressurisation. Most eruptions are preceded by one or multiple episodes of 'volcanic unrest' as magma moves towards the Earth's surface (Acocella et al., 2015; Parks et al., 2015). The movement of magma through the crust (and its interaction with hydrothermal systems) causes pressure changes, which result in ground deformation and earthquakes, and also induces detectable changes in mass and/or density (Freymueller et al., 2015). During magma ascent, volatiles (gases) separate and are either retained in the magma as bubbles or escape to interact with the hydrothermal system or be released at the surface. (Aiuppa et al., 2013). An episode of volcanic unrest may last for a matter of days to a number of years (average ≈500 days), and understanding the processes driving unrest and eruption is an essential part of effective early warning (Cashman et al. 2013, Sparks and Cashman 2017). Volcanoes that erupt infrequently (e.g. calderas) may experience many episodes of unrest (e.g. De Natale

FIGURE 3.8

Maximum known Volcanic Explosivity Index (0-8) of eruptions at European volcanoes in the past ≈10 000 years, based on the Smithsonian Institution Volcanoes of the World database (VOTW4.22). Volcanoes with unknown eruption histories are marked as black triangles.
Source: Smithsonian Institution (2013)



et al., 2006). In contrast, in a global study of 228 volcanoes active between 2000 and 2011 (many of which erupt frequently) the 'Volcanic unrest in Europe and Latin America' project (VUELCO) funded by the European Union's 7th Framework Programme (FP7) showed that 47 % of documented periods of volcanic unrest led to an eruption (Phillipson et al., 2013). Some episodes of detected unrest may not be caused by magma and may be entirely tectonic or caused by hydrothermal phenomena (e.g. Segall, 2013; Biggs et al., 2009).

3.2.2 Monitoring systems and early warning

Volcano observatories are the official institutions in charge of monitoring volcanoes. They may be dedicated to a single volcano (e.g. the Montserrat Volcano Observatory) or may operate from national institutions and be responsible for multiple volcanoes in a country (e.g. the Icelandic Met Office and Istituto Nazionale di Geofisica e Vulcanologia). Some institutions have responsibility for volcanoes and volcano observatories overseas (e.g. Institut de Physique du Globe de Paris).

Volcano observatories have a key role in early warning. They collect multiple streams of diverse data, analyse the data in near real-time, determine the level of threat and make decisions on, for example, raising alert levels (Villagrán de León, 2012). These decisions must be based on sound evidence (Marzocchi et al., 2012; Bretton et al., 2015). The quality, range and sophistication of monitoring methods has increased dramatically in recent years (Sparks et al., 2012), with advances in computing underpinning improvements in power, speed, data transmission, data analysis and modelling techniques. Long-term monitoring at quiescent volcanoes is necessary to establish baselines, and satellite remote sensing provides many opportunities as the spatial and temporal resolution of data improves (e.g. Harris et al., 2016; Bagnardi et al., 2016). Nevertheless, only a small fraction of the world's 1 550 volcanoes have sufficient ground monitoring and the necessary accompanying institutional capacities to effectively support DRM, despite evidence that volcano monitoring is cost-effective (Newhall et al., 1997).

3.2.2.1 Geophysical monitoring (seismic, deformation, gas, infrasound) and the need for global monitoring

Episodes of unrest are highly variable in character, so forecasting the onset of an eruption remains a significant challenge (Chiodini et al., 2016; Selva et al., 2015; Marzocchi and Bebbington, 2012; Sigmundsson et al., 2010). Accelerating rates of seismicity and deformation may be detected before eruptions (Sigmundsson et al. ,2010; Saltogianni et al., 2014; Cannavò et al., 2015) and tracking the location of volcano-tectonic earthquakes in near real time (Thorkelsson, 2012; Sigmundsson et al., 2015, Pallister and McNutt, 2015; Falsaperla and Neri, 2015) may facilitate eruption forecasting. Long-period earthquakes and micro-earthquakes can be key indicators of imminent eruption, especially during an ongoing eruption (McNutt et al., 2015). Cyclic patterns of activity can also enable forecasting of hazardous events (Voight et al., 1999; Loughlin et al., 2002). Borehole strainmeters have successfully been used to forecast eruptions of Hekla in Iceland (Roberts et al., 2011).

If appropriate monitoring is in place at a volcano, it may be possible to issue short-term forecasts of eruptions and volcanic activity and to provide early warnings for different hazards.

Although satellite passes are not yet frequent enough to use Interferometric Synthetic Aperture Radar (InSAR) as a forecasting tool, it can be used in combination with other data to gain tremendous insights into volcanic unrest and eruption (e.g. Gudmundsson et al., 2016; Spaans and Hooper, 2016). InSAR is useful to detect deformation at remote volcanoes and at regional scales (Biggs et al., 2014; Parks et al., 2015).

Gas emissions (Silva et al., 2015; Aiuppa et al., 2013; Chiodini et al., 2015), the chemistry, temperature and level of crater lakes and groundwater (Hernández et al., 2007), and the geochemistry and flow rates of glacial rivers (Kristmansdóttir et al. ,1999) may all show detectable changes before and during eruptions. Gas emissions can be monitored using ground-based, airborne or satellite remote sensing (Aiuppa et al., 2007, 2010; Nadeau et al., 2011; Conde et al., 2013). The gas most easily detected and monitored in the atmosphere during eruptions is sulphur dioxide (SO2) (Oppenheimer et al., 2013; Flower et al., 2016).

Petrology and geochemistry can be used in near real time to characterise eruptive materials and understand magmatic properties and dynamics (Hartley et al., 2016; Pankhurst et al., 2014). Rapid analysis of tephra can detect whether or not there is a magmatic component to phreatic (steam-driven) eruptions (Suzuki et al., 2013).

Environmental monitoring such as dissolved constituents in rainwater, ash leachates (Witham et al., 2005) and particulate (air quality) monitoring can potentially provide information about both eruptive behaviour and probable impacts on health, the environment, infrastructure and buildings (Gislason et al., 2015).

3.2.2.2 Additional and emerging monitoring methods

Volcanic infrasound is a technique that detects, locates and characterises shallow or aerial acoustic sources at volcanoes (Fee and Matoza, 2013; Ulivieri et al., 2013). During the H2020 Atmospheric dynamics Research InfraStructure in Europe 2 (ARISE2) project, episodes of lava fountaining at Etna were recorded ≈600 km away, providing evidence that near-real-time notification of ongoing volcanic activity at a regional scale can be achieved (Johnson and Ripepe, 2011; Marchetti et al., 2016).

Establishing mass eruption rate (a parameter needed to effectively forecast ash dispersal) and characterising ash clouds in near real time is a current challenge (Ripepe et al., 2013; Lamb et al., 2015; Marzano et al., 2013, 2016). Monitoring the extrusion rate of lava is crucial to anticipate the evolution of active lava flow fields or stability of lava domes. Time series digital elevation models (DEMs) collected by satellite at Merapi volcano in 2010 (through the International Space Charter), combined with ground monitoring, enabled increasing extrusion rates to be identified, leading to a rise in alert level and timely evacuations that saved thousands of lives (Surono et al., 2012; Pallister and Surono, 2015). Extrusion rates can be established from the ground, unmanned aerial vehicles or aircraft using a variety of methods (e.g. Wadge et al. 2014a, 2014b; Harris et al., 2005).

Characterisation of heat sources (Figure 3.9) during volcanic unrest and eruption can support scientific understanding of eruptive behaviour and timely response (Harris et al., 2016). During the 2014-15 Bárðarbunga eruption in Iceland, the Middle InfraRed Observation of Volcanic Activity (MIROVA) system (Coppola et al., 2015) was used to chart the evolution of the eruption when access was limited and visibility was poor.

In seismology, deterministic eruption forecasting based on the failure forecast method (FFM) is showing potential (Boué et al., 2016).

Time series observations of volcanoes and their emissions using static or video cameras can yield important insights into hazardous processes. Citizen science, including community

FIGURE 3.9

Measuring the temperature of pyroclastic flow deposits in Montserrat (block and ash flow deposits).
Source and Copyright BGS/Government of Montserrat

monitoring, can fill observational and information gaps, raise awareness of hazards and risk, and engage communities at-risk (e.g. Stevenson et al., 2013; Stone et al., 2014; Wallace et al., 2015). During the 2014-15 eruption at Bárðarbunga volcano, Iceland, people could document their experiences of poor air quality due to the gas-rich eruption online (IMO, n.d).

WOVOdat is a searchable, web-accessible global relational database containing time-series monitoring data from more than 100 eruption episodes; this will allow global trends in unrest and eruption data to be interrogated to assist forecasting at individual volcanoes (Venezky and Newhall, 2007; Widiwijayanti et al., 2015).

3.2.2.3 Communication, reporting and alert levels

During unrest or eruption, scientists communicate in a variety of ways (reports, forecasts, alert levels) using a variety of media (email lists, short message service (SMS), social media, television and radio) to suit the needs of information users (Solana et al., 2008; Haynes et al., 2008a; Mothes et al., 2015). Such users are diverse and include civil aviation authorities, civil protection authorities, businesses, tourist operators, the media and the public. Ideally, the content and format of such communications are tailored to users' needs (e.g. Lechner et al., 2017; Doyle et al., 2014) and users have considered in advance their thresholds for action (e.g. Marzocchi et al., 2012; Hicks et al., 2014). During an emergency, joint formal reports can be particularly effective if scientists and civil protection authorities work well together, and if the content and format has been designed specifically with users in mind (e.g. Scientific advisory board of the Icelandic Civil Protection, 2015).

A volcano Early Warning System (EWS) requires that monitoring data are collected and interpreted by scientists, the level of threat is determined

FIGURE 3.10

Summary of alert levels and civil protection system response for Vesuvius volcano, Italy. Alert levels are established by INGV Vesuvio based on changing monitoring parameters. The civil protection system responds in each operative phase according to the alert level and the emergency plan.
Source: authors

ALERT LEVEL	STATE OF THE VOLCANO	ERUPTION PROBABILITY	TIME OF ERUPTION	OPERATIVE PHASE
Base	No significant variation of monitored parameters.	Very low	Undefined	
Caution	Significant change of monitored parameters.	Low	Indefinite, or not less than several months.	I Caution
Warning	Further significant change in monitored parameters.	Medium	From months to weeks	II Warning
Alarm	Appearance of phenomena and/or evolution of monitored parameters suggesting a pre-eruption dynamic.	High	From weeks to days	III Alarm

Operative Phase I: Verification of contingency plans, constant contact between scientists and civil protection, checking of functionality and immediate availability of resources, infrastructure and services needed for subsequent alert levels.

Operative Phase II: Voluntary evacuation of red zone to alternative accommodation outside the zone of risk. All involved in the emergency plan alert and prepared for Phase III.

Operative Phase III: Evacuation of the red zone within three days.

and a decision to alert stakeholders is made (Fearnley, 2013). Some volcano observatories use Volcanic Alert Levels (VALs) to communicate changes in the status of volcanic activity that imply a changing probability of eruption (Gardner and Guffanti, 2006; Fearnley, 2013; Winson et al., 2014) or changing types of hazard (Potter et al., 2014). Notification of a change in VAL is usually accompanied by situation-specific information in the form of a more detailed report. VALs are developed to suit local situations and, as such, they vary worldwide. Some focus on unrest and eruption forecasting (Figure 3.10) and others acknowledge the changing phenomena and hazards of long-lived eruptions (Potter et al., 2014). In situations in which major and costly mitigation actions are triggered by volcanic EWSs (e.g. the evacuation of urban areas), quantitative, objective and rational scientific decision-making is essential to avoid accusations of 'false alarms' (see Chapter 3.2.3, Hincks et al., 2014).

The global network of nine Volcanic Ash Advisory Centres (VAACs) was set up by the International Civil Aviation Organization (ICAO) following aircraft encounters with ash clouds in the 1980s (Guffanti et al., 2010). Volcano observatories provide reports to VAACs to support the initiation of ash dispersal models and have the option to set an 'aviation colour code' representing the status of volcanoes in the context of likelihood of eruption and potential for ash emissions (Lechner et al., 2017). This system can run in parallel to a VAL system.

In situations on the ground in which it is acknowledged that there may be little time for response , alerts may be sent out to authorities and the public via SMS, telephone, radio or social media (e.g. IMO, 2016; Stone et al., 2014; Mothes et al., 2015). EWSs for lahars and jökulhlaups (glacier floods in Iceland) are variable in terms of components but, in general, require monitoring (e.g. acoustic flow monitors) to detect flows in proximal environments that can alert authorities to sound sirens downstream so that communities can be evacuated.

3.2.3 Volcanic hazard assessment

Volcanic hazards are diverse and they can occur in different combinations and interact in different ways throughout the unrest, eruption and post-eruption period.

Volcanoes generate multiple hazardous processes, the short- and long-term forecasting of which involve diverse methods to anticipate hazard footprints in order to enable anticipation and mitigation of impacts.

Scientists are improving their ability to assess and forecast these hazards, their likely 'footprints', interactions and impacts over different timescales. Short-term and long-term forecasts, to support crisis response and planning, respectively, are based on a variety of different approaches depending primarily on data availability. Deterministic and probabilistic approaches to hazard are used and are appropriate in different circumstances. .

3.2.3.1 Hazard forecasting

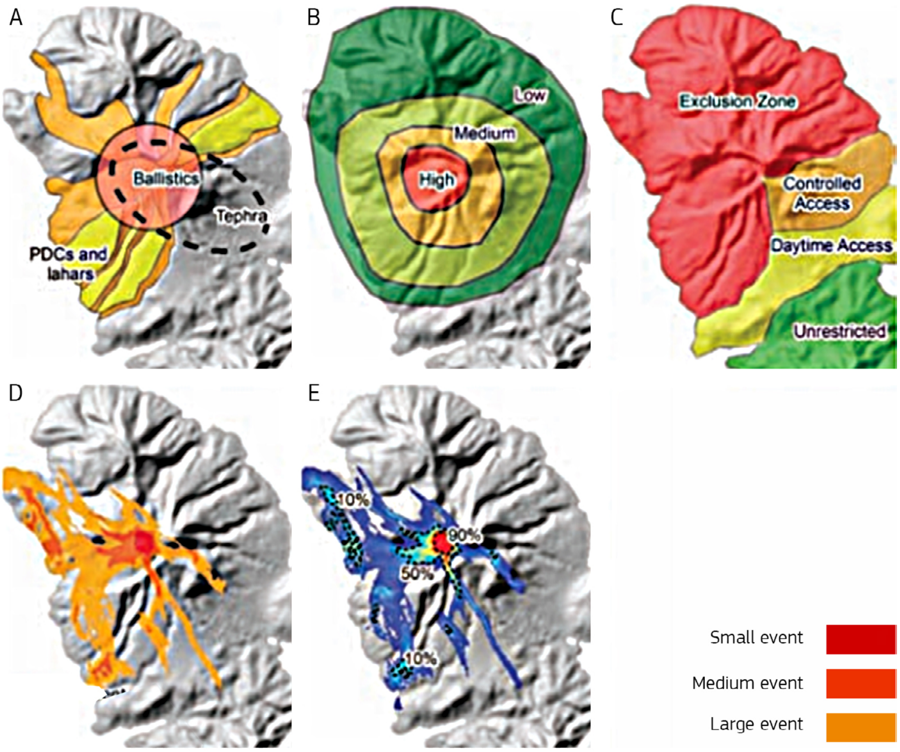
Short-term forecasts can enable communities across broad areas to prepare for imminent hazards and impacts. For example, simple simulations of expected atmospheric dispersal and deposition of volcanic tephra based on monitoring/observation parameters, can be made available (e.g. for Etna at INGV (n.d.) and for Mount St Helens at USGS (2015), Hasegawa et al., 2015). Similarly, short-term dispersal forecasts of SO_2 (which may adversely affect human and live-stock health) can enable mitigation actions to be taken (e.g. Gislason et al., 2015). Such forecasts can also be achieved for lava flows and lahars, and, in some places, mitigation of lava flow impacts has been attempted using engineering measures.

Volcanic hazard process models still need further development to better simulate key processes; this is especially true for pyroclastic flows, surges and lahars, the assessment of which currently lags behind that of tephra dispersal and fall. The ability to model interacting hazards is also important, such as rainfall-triggered lahars (Jones et al., 2015), eruption column collapse into pyroclastic flows or pyroclastic flows into lahars.

Long-term volcanic hazard assessment is primarily based on characterising the past eruptive activity of a volcanic system and understanding the recurrence rates of eruptions and the range of possibilities for future eruptions. Such assessments are often presented as hazard maps. Ideally, geological and historical studies are needed to establish eruption histories but sometimes such information is not available, further fieldwork is needed, or data simply doesn't exist. For example, fine-grained deposits (e.g. ash fall, surges, lateral blasts) may be missing from the geological record, so thorough consideration of knowledge gaps and uncertainties is paramount in any hazard analysis (e.g. Engwell et al., 2013; Sparks et al., 2013, Bonadonna et al. 2012, 2015). Volcanologists can study analogue volcanoes and global databases to address knowledge gaps (e.g. Ogburn et al., 2015), or use methods such as expert elicitation in order to consider and quantify uncertainties (Aspinall, 2006, 2010). Uncertainty should be acknowledged in all scientific decision-making, forecasts and assessments.

FIGURE 3.11

Synthetic examples (not a real volcano) of the appearance of five hazard map types found during the review:
(a) geology-based map,
(b) integrated qualitative map,
(c) administrative map,
(d) modelling-based map and
(e) probabilistic map.



3.2.3.2 Volcanic hazard maps

Volcanic hazard maps can communicate information about one or a range of hazards including lahars, pyroclastic flows and surges, tephra fall (Macedonio et al., 2008), ballistics, lava flows (Richter et al., 2016), and, sometimes, less frequent hazards such as debris avalanches and monogenetic eruptions. An International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) working group is reviewing current global practice (>200 published hazard maps). They defined five major classes of hazard map and found that >60 % of maps are based primarily on the geological history of the volcano (Figure 3.11), despite incomplete eruption histories that do not represent all past and possible future scenarios. Furthermore, >83 % of hazard maps use a qualitative 'high-medium-low' description to indicate likelihood of impact, but the meanings behind these terms are open to broad interpretation (Calder et al., 2015).

The IAVCEI working group have established that there is no single approach that suits all situations; different approaches may be suitable for different needs. Nevertheless, there is consensus that quantitative, accountable and defendable hazard maps are increasingly needed.

The group aims to collectively define

good practices. Scientific priorities to enhance hazard maps include (1) improved methods for probabilistic analysis, especially for lahar, pyroclastic flows and surges, (2) establishing methods to undertake hazard assessments for data-poor volcanoes and (3) approaches for multihazard, multiscenario probabilistic modelling (Calder et al., 2015). Although probabilistic volcanic hazard maps exist for a few of the world's best studied volcanoes, they are far from being the norm.

Haynes et al. (2007) recognised that maps are rarely well understood by users and that three-dimensional (3D) visualisation can significantly help understanding.

3.2.3.3 Probabilistic volcanic hazard assessment

A variety of methods are used, often in combination, to generate probabilistic volcanic hazard assessments over different timescales.

For example, statistical methods can be used to assess recurrence rates and locations of vents, which, when combined with numerical simulations of volcanic processes (e.g. lava flow emplacement, tephra dispersal and fall), can create hazard curves for specific locations or hazard maps for larger areas (Connor et al., 2015). There may be high uncertainty in vent location, particularly if a volcano has vents distributed across its flanks or the area is a volcanic field comprising multiple eruption centres (Connor et al., 2012; Bebbington and Cronin, 2010).

Because of the variety and potential complexity of volcanic hazards, probabilistc hazard maps commonly attempt to communicate information about only a single hazard at a time (Figure 3.11e). For example, volcanic flows are tyically displayed as the spatial variation of inundation probability over a given period of time. Tephra fall might be assessed using contours of probability given a hazardous threshold of tephra thickness (Jenkins et al., 2015a) or contours of tephra thickness given a certain probability in order to better assess the associated impact (e.g. Bonadonna, 2006; Biass et al. 2014, 2016a). Probabilistic hazards assessments can be local to global in scale.

The first probabilistic assessment of global tephra fall hazard has been attempted for the 2015 United Nations International Strategy for Disaster Reduction (UNISDR) Global Assessment Report, based on a method developed for the regional scale (Jenkins et al., 2012, 2015a).

Once volcanic unrest begins there are multiple potential eruptive outcomes (scenarios) due to the dynamic complexity of volcanic systems. In this situation, probabilistic methods provide a basis for scientists to explore those outcomes, allocate probability estimates to them (Marzocchi et al., 2012; Selva et al., 2010) and communicate them to authorities to support rational decision-making (e.g. Sparks 2003, Marzocchi et al., 2007). The results can be tested using statistical procedures and allow comparisons between volcanoes and other natural and non-natural hazards (e.g. Scandone et al., 1993; Bayarri et al., 2015).

Current probabilistic approaches build on the idea of event trees (Newhall and Hoblitt, 2002) and on Bayesian statistics (e.g. Papadopoulos and Orfanogianaki, 2005). The probability estimates allocated to each outcome/scenario might be empirical, or be based on expert discussion and elicitation, numerical simulations or a combination of methods (e.g. Aspinall, 2006, 2010; Marzocchi and Bebbington, 2012). These methods are also useful if applied regularly at long-lived or frequently active volcanoes where probabilities change and assessments can be compared over time (Pallister et al., 2010; Wadge and Aspinall, 2014). Similar approaches have now been applied at Vesuvius (Neri, 2008), Teide-Pico Viejo, Tenerife (Martí et al., 2008), and Auckland Volcanic Fields, New Zealand (Lindsay et al., 2010). The same principle has also been developed to generate tools (e.g. Marzocchi et al., 2008).

3.2.4 Volcanic risk assessment and mitigation

3.2.4.1 Vulnerability and exposure

Vulnerability is complex, dynamic and spatially variable with many facets including systemic, social, functional and economic vulnerability (e.g. Enhancing resilience of communities and territories facing natural and na-tech hazards (ENSURE) project, Menoni et al., 2012). Exposure contributes to vulnerability (Cutter 2013) and includes the people and assets exposed to the hazards. Volcanic unrest and eruptions tend to unfold over weeks to years, thereby enhancing the dynamic complexity of factors that contribute to vulnerability and exposure (Galderisi et al., 2013; Zuccaro et al., 2014).

Volcanic tephra fall is the hazard that most frequently affects large populations and assets and has reasonable vulnerability estimates in risk models (Spence et al., 2005; Jenkins et al., 2015). Jenkins et al. (2014), as part of the Mitigate and Asses risk from Volcanic Impact on Terrain and human Activities (MIA-VITA) project, developed guidelines and methodologies for carrying out initial physical vulnerability assessments. This built on previous projects including the SPeeD project at Vesuvius and the EXPLORIS project (e.g. Zuccaro et al., 2008; Marti et al., 2008). Jenkins et al. (2015) categorised tephra fall impacts by sector and considered the relationship between hazard intensity (in that case ash thickness) and damage or disruption to each sector (buildings, critical infrastructure, agriculture). More data need to be collected to inform estimates of physical vulnerability of buildings and infrastructure, through: (1) collection of post-eruption damage data (e.g. Baxter et al., 2005; Wilson et al., 2011; Biass et al., 2016a, 2016b; Charbonnier et al., 2013; Jenkins et al., 2015b), (2) experimental testing of materials failure, or (3) using theoretical calculations of material strengths (e.g. Jenkins et al., 2014). Damage data and experimental data remain sparse so theoretical calculations can contribute to the development of vulnerability functions, which provide the probability of a certain level of damage as a function of hazard intensity (Jenkins et al., 2014; see also Chapter 2.4).

A dynamic pressure scale for building

FIGURE 3.12

Soufrière Hills Volcano and Plymouth, the capital of Montserrat, in October 1997.

damage by pyroclastic surges (Baxter et al., 2005), developed after experiences in Montserrat (Figure 3.12) and at Mount St Helens, has contributed to simulation work at Vesuvius and other European volcanoes in the EXPLORIS project (Baxter et al., 2008).

Studies on social vulnerability in volcanic risk are increasing in number and showing the value of semi-quantitative and qualitative assessments (e.g. Sword-Daniels, 2011; Sword-Daniels et al., 2014). Hicks and Few (2015) showed that during long-term eruptions, coping capacity, maintenance of well-being, recovery of losses and rebuilding of livelihoods are highly variable within populations and tend to be linked to preceding socioeconomic conditions (Birkman, 2007). Socio-economic impacts are most likely to be experienced by those with pre-existing and inter-related sociocultural, political and economic vulnerabilities (Wisner et al., 2012; Gaillard 2008). Volcanic activity can have a disproportionate effect on livelihoods and economy because of high systemic vulnerability (Wilson et al., 2011, 2014; Jenkins et al., 2015a).

Comprehensive quantitative assessment of the impacts of all types of volcanic hazard is relatively new but is most advanced for tephra fall (Craig et al., 2016; Elissondo et al., 2016; Wilson et al., 2011, 2012, 2014; Magill et al., 2013). Socioeconomic impacts due to tephra fall are most likely to be documented in long-lived eruptions (e.g. Sword-Daniels, 2011; Sword-Daniels et al., 2014).

3.2.4.2 Risk assessment methodologies

Volcanic risk assessment is not as advanced as assessment of other hazards such as flooding, earthquakes and tropical cyclones. For the long-lasting eruption at Soufriere Hills Volcano, Montserrat, volcanic risk has been assessed in a regular and consistent way for 20 years (Aspinall et al., 2002; Aspinall, 2006; Wadge and Aspinall, 2014). After deriving event scenario probabilities and their uncertainties by elicitation, risks and uncertainties are quantified using Monte Carlo modelling, and the risk is presented as (1) societal risk expressed quantitatively as a curve of the probability of exceeding a given number of fatalities, (2) individual risk given as an annualised probability of death (from the volcano) for any person living in a specific area and (3) occupational risk given for people working under certain conditions in specific areas.

An example of a volcanic risk model is the KazanRisk loss model (riskfrontiers.com/kazanrisk.htm), which uses numerical dispersal modelling of ash fall in Greater Tokyo to estimate potential losses associated with building damage, clean-up and reductions in agricultural productivity. At regional to global scales, the CAPRA risk modelling platform (ecapra.org) has been used to provide preliminary estimates of potential building damage around active volcanoes in the Asia-Pacific Region using simplified volcanic hazard outputs from a statistical emulator (Jenkins et al., 2015a). Because some crucial aspects of vulnerability must be assessed qualitatively, there is a need to find innovative ways to integrate qualitative with quantitative data to assess volcanic risk (Hicks and Few, 2015). Novel interdisciplinary approaches are now being developed (e.g. STREVA project) that combine volcanological techniques, probabilistic decision support and social science methods to ensure that the benefits of even uncertain and incomplete knowledge are acted upon to reduce risk (e.g. Hicks et al., 2014; Barclay et al., 2014). Stirling (2010) highlighted that different analytical methods suit different epistemic conditions and acknowledging the state of knowledge is a good start in enabling effective risk analysis and communication..

'Forensic analysis' of past disasters provides a strong basis for learning (e.g. Voight 1990, Loughlin et al. 2002, Thordarson and Self, 2003; Bird et al., 2010; Ragona et al., 2011), and longitudinal studies can reveal valuable insights into causal processes behind impacts and disasters (e.g. Integrated Research on Disaster Risk FORIN project 2011). Such approaches are also being applied to understand recovery processes that are complex and can last for decades (Sword-Daniels et al., 2015).

3.2.4.3 Civil Protection, scientists and risk management

Volcano observatories and civil protection authorities, working together as well as with the public, have reduced fatalities due to volcanic activity worldwide. At least 50 000 lives were saved in the 20th century (Auker et al., 2013) and even more have been saved since 1985 (Voight et al., 2013).

Mutual understanding and trust develop with an investment of time and effort (Haynes et al., 2008a, 2008b) and it is too late to start when an emergency begins. Effective communication and decision-making during a rapidly changing emergency situation (Fischoff, 2013; Doyle et al., 2014) will be facilitated by good planning, preparation and response protocols (Doyle et al., 2015; Bretton et al., 2015). Interdisciplinary and transdisciplinary approaches can bring a wide range of methods and experiences together (e.g. communities, scientists, authorities) to facilitate better understanding, analysis and communication of hazard and risk (Hicks et al., 2014; Barclay et al., 2014, 2015).

Volcanic unrest and eruptions can be prolonged, which may cause disruption and have long-term socioeconomic impacts. Tephra fall can cause damage and disruption across sectors and has potential health impacts (Horwell and Baxter, 2006; Carlsen et al., 2012); therefore, planning for clean-up and recovery is essential (Hayes et al., 2017).

Preparedness for volcanic unrest and eruption often takes the form of contingency plans,which can be practised (Figure 3.13) by scientists, authorities and other stakeholders, including the public (Hicks et al., 2014). Different types of exercises have been reported around the world (Figure 3.13), ranging from the training of small groups to international reaction-chain exercises (Lindsay et al., 2010; Ricci et al., 2013). In high-risk urban settings (e.g. Naples), there are significant costs to mitigation actions, even to exercises, so direct and indirect costs and benefits need to be carefully considered to support decision-making (Marzocchi et al., 2012; Woo, 2014).

FIGURE 3.13

An evacuation exercise for the entire population of Tristan da Cunha, South Atlantic.
Source: photograph courtesy of Anna Hicks

The 2010 eruption of Eyjafjallajökull volcano in Iceland demonstrated that even small eruptions can have global impacts (Ragona et al., 2011). Therefore, international collaboration is essential to ensure that lessons learned and scientific progress are translated into planning and preparation across all sectors (Schmidt et al., 2011, 2015; Bonadonna et al., 2012).

3.2.5 Conclusions and key messages

Partnership

Long-term collaboration and effective partnerships between scientists (operational and research) and civil protection authorities are particularly important for effective evidence-based risk management and emergency response. The recent FUTUREVOLC and MEDSUV projects (FP7) showed how Europe-wide research partnerships can support such national and Europe-wide DRM efforts in particular. Engagement with users of scientific and civil protection advice can improve the format and content of outputs, enhancing understanding, uptake and effective decision-making at all levels. The knowledge and experience of those at risk is increasingly recognised as important and their involvement in the design and development of DRM strategies can be highly effective.

Knowledge

Hazard, impact, vulnerability, loss and recovery data are sparse in volcanology but are needed to produce better hazard and risk assessments. Detailed study of all future eruptions and their impacts is needed. Despite an overall need for increased quantification in volcanic risk, interdisciplinary collaboration is recommended to capitalise on both quantitative and qualitative approaches to risk, particularly in situations in which data are scarce. Progress in process understanding is needed to enable better anticipation of hazardous events. Frameworks for the optimal combination of hazard and vulnerability analysis across multiple temporal and spatial scales is needed for comprehensive risk assessments and proactive policies of risk reduction.

Innovation

There is an ongoing need for development in monitoring techniques, integrated analysis of ground and space data, hazard and vulnerability assessment methodologies and interdisciplinary/transdisciplinary science. A next important step for the volcanology community as a whole is to enhance innovation in hazard and risk assessment strategies. There is an increasingly urgent need for near-real-time global monitoring and a reporting platform to support the anticipation of volcanic events that have wide-reaching or humanitarian impacts. This will require collaborative approaches and innovative integration of data in a wide variety of formats and at different spatial and temporal resolutions.

3.3 Geophysical risk: tsunamis

Gerassimos A. Papadopoulos, *Stefano Lorito, Finn Løvholt, Alexander Rudloff, François Schindelé*

3.3.1 Tsunamis in the global ocean

3.3.1.1 Tsunami physics, generation mechanisms and impact

The word tsunami comes from the Japanese for 'harbour wave'. Tsunamis are sea waves with periods that typically range from a few minutes to about 1 hour. The wavelength ranges from tenths to hundreds of kilometres depending on the causative source. The majority of tsunamis (≈80 %) are produced by submarine earthquakes that are characterised by a shallow focus (≤100 km), a large magnitude and a faulting mechanism with a significant vertical component. Volcanic eruptions and landslides also produce tsunamis. Subduction zones (i.e. major lithospheric plate boundaries) are particularly prone to tsunami generation (e.g. Figure 3.14). Meteorological effects may also cause wave phenomena resembling tsunamis (meteotsunamis).

In the deep ocean, tsunami speed depends on the water depth, D. At first approximation, the shallow water wave speed C is:

$$C = \sqrt{gD} ,$$

where g is gravity acceleration.
In deep water, the wave amplitude may remain small, typically ranging up to a few metres. The waves become higher and shorter in shallow water and may have run-up heights that exceed several tens of metres (Figure 3.15); exceptional landslide tsunamis have even been recorded that reach several hundreds of metres vertically (Miller et al., 1960).

Tsunamis may have catastrophic consequences, such as loss of life, destruction of infrastructure, buildings and vessels, and economic and social impacts, the last of which may be felt both locally and remotely. In total, 16 major tsunamis killed 250 900 people in 21 countries between 1996 and 2015 (UNISDR/CRED 2016). The great Sumatra tsunami of 26 December 2004, which was caused by an M9.3 magnitude earthquake, caused the deaths of 226 000 people in 12 Indian Ocean nations (Figure 3.16).

Tsunamis are long-period sea waves generated by earthquakes, volcanic eruptions and landslides. They may have large wave heights in coastal zones, and can cause destruction to populations, infrastructures, properties and the natural environment.

The Tohoku tsunami of 11 March

2011 that hit north-east Japan (Pacific Ocean) following an M9.0 earthquake was also devastating (Figure 3.17). The maximum run-up exceeded 40 metres, and the tsunami penetrated more than 5 km inland in places. The estimated total death toll was about 19 000 people, nearly 90 % of whom died as a result of the tsunami. The direct economic loss was reported to be USD 210 billion (EUR 198 billion), which was orders of magnitude higher than for the 2004 Sumatra tsunami, the cost of which was estimated to be USD 4.4 billion ((EUR 4.1 billion) (Løvholt et al., 2015). The Fukushima nuclear power plant was damaged by the tsunami and there was a meltdown of three reactors.

For earthquakes, intensity is an estimation of the event impact, which is measured using empirical scales such as the 12-grade Mercalli–Sieberg scale, which was introduced more than a century ago and is gradually improving. Magnitude measures earthquake size in terms of the energy released. Richter (1935) introduced an initial magnitude scale, which was later improved by the concept of moment-magnitude (Kanamori, 1977). However, no standard and satisfactory tsunami magnitude scales have been proposed so far owing to the lack of appropriate tsunami instrumental records. Therefore, tsunami intensity, expressing the event impact (e.g. using the six-grade tsunami intensity scale introduced by Sieberg (1927)), is still a rough proxy of the event size. A 12-grade scale was introduced by Papadopoulos and Imamura (2001), which is similar to the one used in seismology: for example, a tsunami of grade 6 intensity indicates a slightly damaging event, while a grade-10 tsunami is very destructive. However, for tsunami risk and vulnerability assessments, one has to turn to more stringent tsunami metrics, such as the expected tsunami run-up height and onshore flow depth, to calculate possible damage and losses.

3.3.1.2 Major tsunami sources in the Earth

Large tsunamis occur frequently along the ‘Ring of Fire’ in the Pacific Ocean. Landmark examples include the 1960 (Chile), 1964 (Alaska) and 2011 (Japan) tsunamis, which were all of a large magnitude and occurred along subduction zones. The large number of tsunamis in the Pacific Ocean (NGDC/WDS, n.d.) are caused by widely different sources, such as non-subduction earthquakes, landslides and volcanoes.

Subduction zone earthquakes also occur in the Indian Ocean, along the Sunda Arc and in Makran (Pakistan). Thrust faulting earthquakes, such as the one that occurred in 2004 in Sumatra, and large volcanic eruptions, such as that of 27 August 1883 in Krakatoa (Sunda Strait, Indonesian Arc), produced devastating transoceanic tsunamis. Tsunamigenic zones are also present in the North-East Atlantic and the Mediterranean (NEAM) region, the Caribbean Sea, Indonesia and the Philippines. Tsunamis can also occur in areas with little earthquake activity.

3.3.1.3 Tsunamis in the North Eastern Atlantic and the Mediterranean region

In the NEAM region, the historical tsunami record is rich thanks to many relevant documents that have been preserved throughout history. Geological evidence both onshore and offshore, such as sediment deposits, boulders having been moved inland and geomorphological changes, has contributed to the identification of paleotsunamis (e.g. Papadopoulos et al., 2014). Apart from a few mega or basin-wide tsunamis, more than 300 smaller tsunamis, either local or regional, have been documented so far (Figure 3.18).

The main geotectonic structure producing tsunamis in the Mediterranean Sea is the Hellenic Arc subduction zone (see Figure 3.14). Large earthquakes (M≈8.5), presumably recurring at intervals of hundreds to thousands of years, generate basin-wide, destructive tsunamis, such as those that occurred in AD 365 and 1303 in Crete, and the large Minoan (17^{th} century BCE) tsunami produced by the giant eruption of the Santorini volcano. Strong tsunamis also occur in less active regions, such as the Algerian thrust (North Africa, e.g. Schindelé et al., 2015), the Calabrian Arc (southern Italy) and the Cyprus Arc. Several other seismic, volcanic and landslide tsunami sources are distributed in the Mediterranean Sea, including in closed basins (e.g. the Corinth Gulf, Central Greece), the Marmara Sea and the Black Sea. In the North-East Atlantic, the area offshore south-west Iberia constitutes a major source of basin-wide destructive tsunamis (e.g. the one caused by the Lisbon earthquake (M≈8.5) on 1 November 1755). However, local tsunamis occur in the Azores Islands, in the English Channel and in Norwegian fjords, the last

FIGURE 3.14

The Hellenic subduction zone of the African lithospheric plate beneath the Eurasian plate in the South Aegean Sea is a cause of tsunami generation from strong submarine earthquakes
Source: Mouslopoulou et al. (2015)

(a) Stars indicate the epicentres of the large tsunamigenic earthquakes of AD 365 (west) and 1303 (east) off the island of Crete. Yellow arrows indicate plate movement from Global Positioning System stations. G, Gavdos Island; WF, Western Fault; GF, Gavdos Fault; EF1, Eastern Fault 1; EF2, Eastern Fault 2.

(b) Subduction cross-sections in western (a-a') and eastern (b-b') Crete. Black line indicates plate interface. The weakly locked portion of the interface is highlighted in yellow (vertical scale changes with depth). A large earthquake in one of the faults of the area causes upward displacement of the crust and pushes the water column upwards, thus producing a large tsunami.

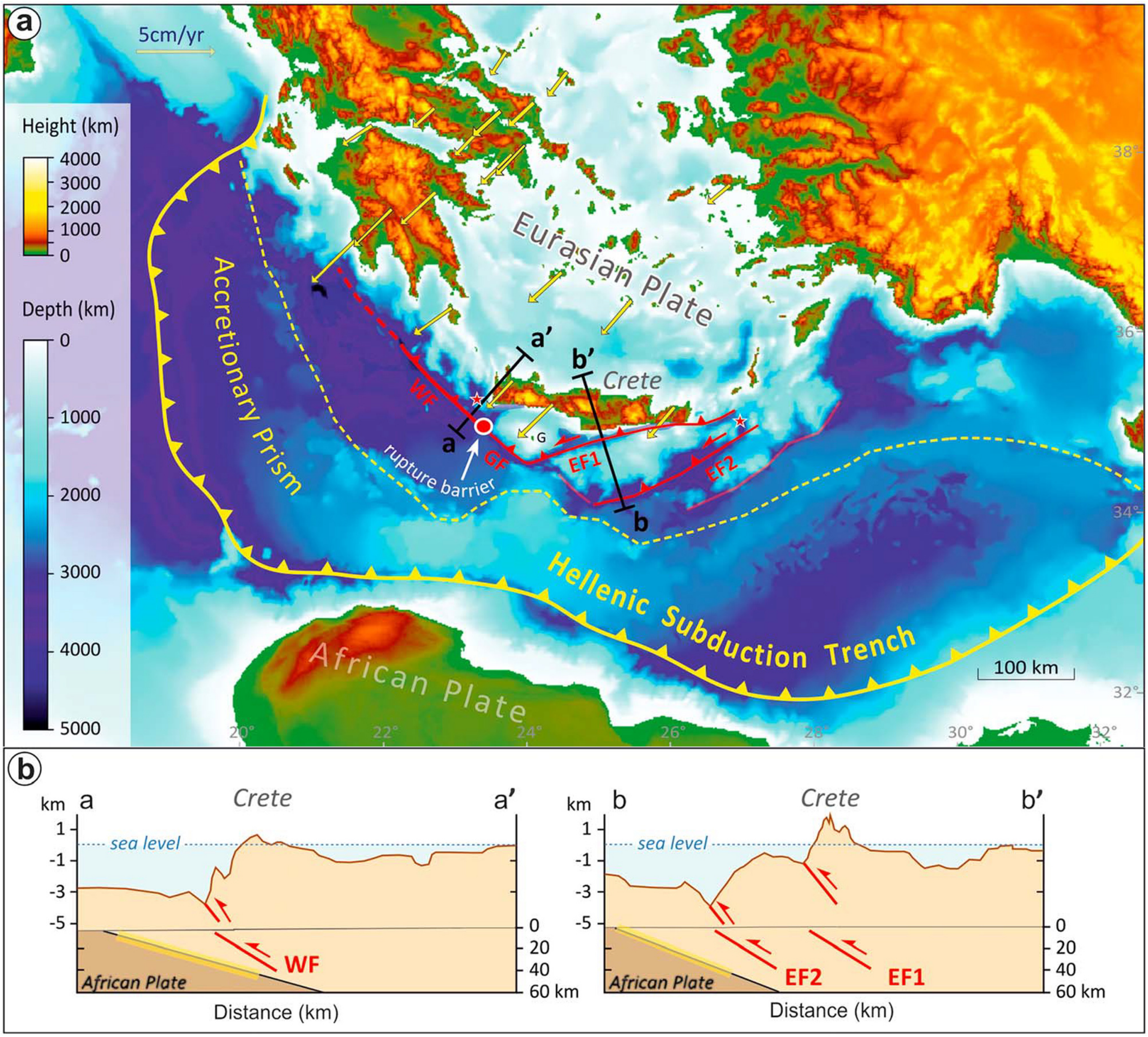


FIGURE 3.15

Schematic explanation of some commonly used tsunami terms.
The term "run-in" is also in use instead of inundation.
The term "tsunami amplitude" is in use by some authors to describe either tsunami height at shore or wave amplitude in the open sea.
Source: Papadopoulos et al. (2014); modified from IOC (1998)

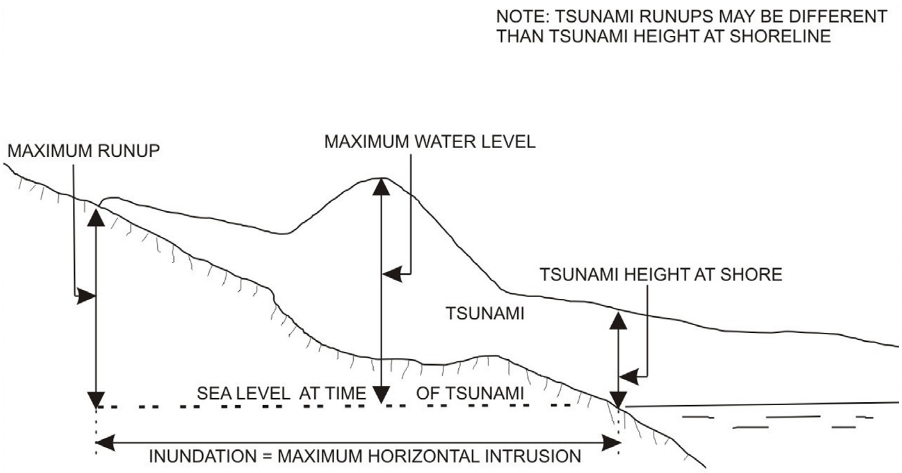


FIGURE 3.16

Brick building in Sri Lanka destroyed by the large Sumatra tsunami of 26 December 2004.
Source: photograph courtesy of G. A. Papadopoulos

of which are associated with coastal landslides.

Nearly all the tsunami sources in the NEAM region are located at a short distance from coastlines, and tsunami travel times are very short, in most cases less than 30 minutes. The near-field issue is of crucial importance for the effective operation of Tsunami Early Warning Systems (TWSs) both in the NEAM region and elsewhere (e.g. Schindelé, 1998).

3.3.2 Monitoring systems

3.3.2.1 Seismograph networks

National institutions maintain their own seismic networks all around the globe, including in the NEAM region, to pursue their main mission of national seismic monitoring. Data archiving and/or real-time data exchange occurs within the framework of international organisations, consortia and federated networks. The sustainability of the European component of these services is supported by national and EU funding and by the European Plate Observing System European Research Infrastructure Consortium, which is a pan-European long-term infrastructure programme. For example, the permanent stations available at the time of writing through the European Integrated Data Archive portal (EIDA, 2017) are illustrated in Figure 3.19. This integration of national networks into a single system allows for a better and more rapid characterisation of strong (M6-6.9) to major and great (up to M8 or more) earthquakes. This important asset feeds a vital data bank that can be exploited for a better understanding of the seismic potential of a region, which is also a fundamental tool for seismic and tsunami monitoring and the long-term assessment of tsunami hazard and risk.

In high-magnitude earthquakes (e.g. Sumatra 2004), the very long rupture duration along the seismic fault makes it difficult to form a rapid assessment of earthquake magnitude, which, however, is a prerequisite for an effective TWS. This is a problem known as 'earthquake magnitude saturation'. The 2004 event spurred the development of ad hoc seismological techniques (e.g. Lomax and Michelini, 2009a, 2009b), including improvements in inversion methods for finite source models (e.g. Shearer and Bürgmann, 2010). In several areas there is a significant gap in coverage due to the lack of sufficient seismic station coverage. This is the case along the coasts of North Africa. In the North-East Atlantic, the coverage is also limited owing to the absence of land areas. These limitations in turn affect the accuracy and rapidity of the assessment of tsunami potential when an earthquake is not surrounded by a sufficient number of nearby seismic stations. Improvements in station coverage would reduce both the number of false alarms and the uncertainty of real-time tsunami forecasting provided by TWSs.

FIGURE 3.17

Large fishing boats that were moved ashore by the Japanese tsunami of 11 March 2011.
Source: photograph courtesy of G. A. Papadopoulos

3.3.2.2 Global Navigation Satellite System networks

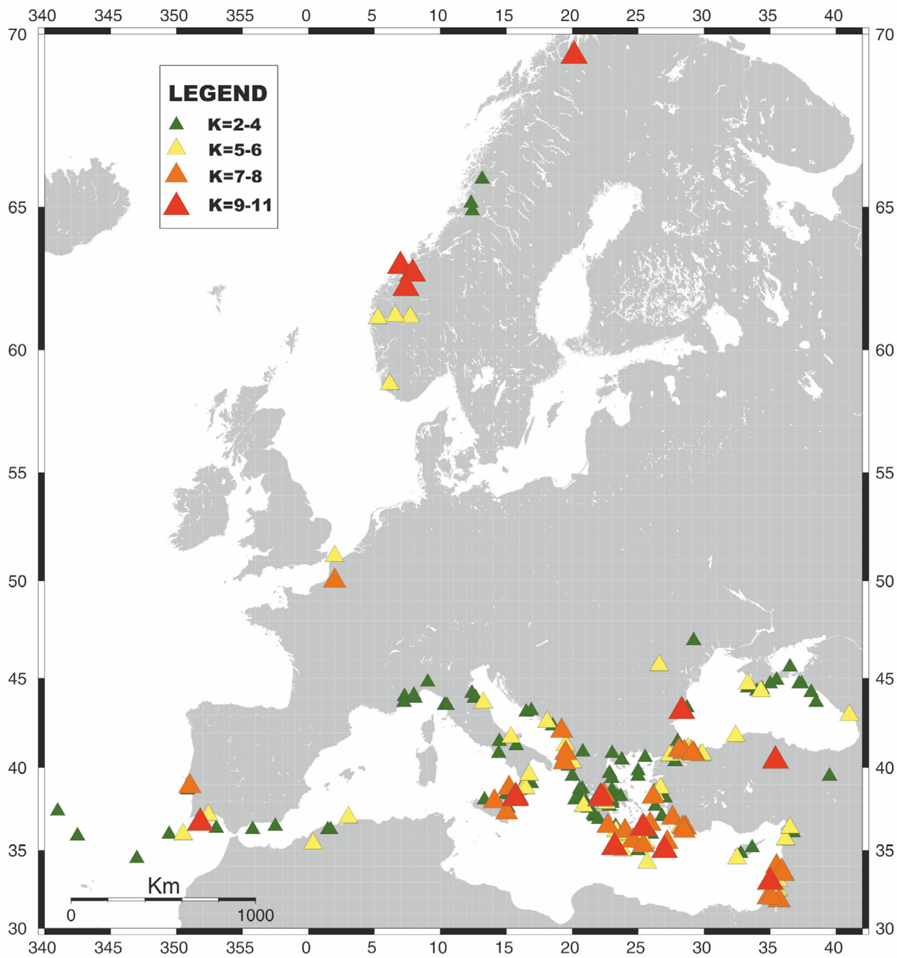
An alternative way to overcome the problem of earthquake magnitude saturation is to use the Global Navigation Satellite System (GNSS) to measure large earthquake magnitudes. The underlying idea is that GNSS stations, which do not saturate when measuring large co-seismic ground displacements, can be closer to the source than the seismic broadband stations, and thus may contribute to faster TWS response times.

The monitoring of earthquakes, crustal deformation and sea-level changes through geophysical networks constitutes the cornerstone for tsunami monitoring and early warning. Innovative solutions are needed for substantial monitoring improvement.

Global Navigation Satellite System is the modern terminology used for geo-spatial positioning systems in general, including Global Positioning System (GPS) and several regional networks (e.g. GLONASS, Galileo, BeiDou). Numerous national and international organisations maintain permanent networks of receivers that contribute to this global system. At a European level, one of the most important is the EUREF Permanent Network (EUREF, 2011), to which more than 100 organisations actively contribute. In addition to their applications in geodesy and geophysics, GNSS data transmitted in real time can significantly improve the earthquake monitoring and tsunami forecasting capabilities of the TWSs. The 2004 Sumatra event triggered worldwide efforts for the augmentation of TWSs with a GNSS-based component (Blewitt et al., 2006; Sobolev et al., 2007; Song, 2007; Falck et al., 2010; Babeyko et al., 2010). Following the 2011 Tohoku tsunami disaster, thanks to the exceptional Japanese GEONET network, it was possible to show the feasibility of a GNSS-based TWS (Ohta et al., 2012; Hoechner et al., 2013). In addition, Chile and the United States, among others, are now actively progressing in the same direction (e.g. Melgar et al., 2016).

FIGURE 3.18

Geographical distribution of the tsunami sources reported in the European-Mediterranean region from antiquity to the present. K is the maximum tsunami intensity in the 12-grade Papadopoulos and Imamura (2001) scale.
Source: Papadopoulos (2015)



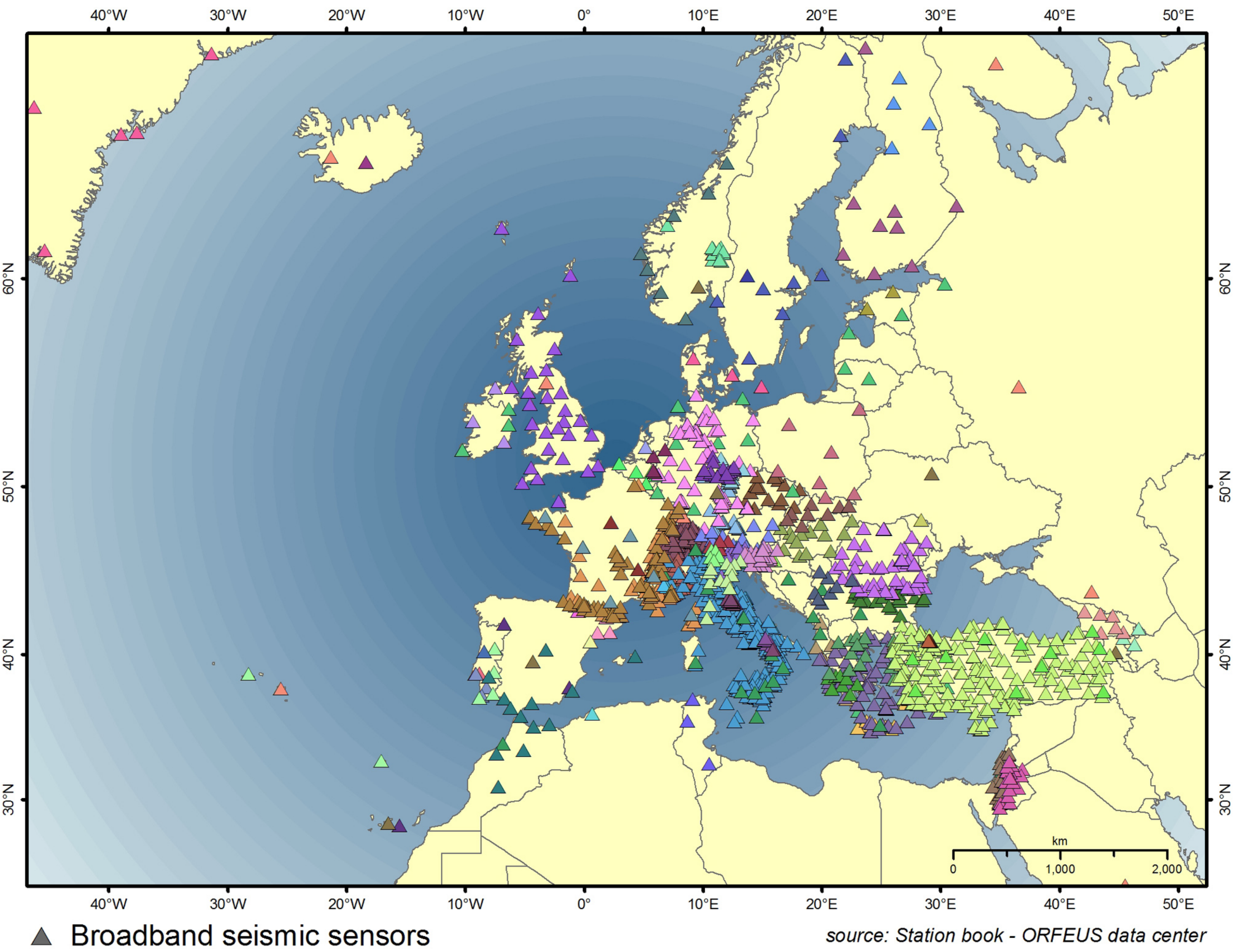
In the Mediterranean, the Istituto Nazionale di Geofisica e Vulcanologia (INGV; Italy) and the National Observatory of Athens (NOA; Greece), as well as other Tsunami Service Providers (TSPs) acting in the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (NEAMTWS/IOC/UNESCO) (see Chapter 3.3.3.4), operate GPS networks transmitting data in real time. These networks provide a good coverage around the Ionian Sea (Figure 3.20), where several potentially tsunamigenic seismic sources are situated (e.g. Basili et al., 2013). In cooperation with GFZ (Germany), these centres are assessing the feasibility of the incorporation of GNSS-based solutions in their operations, within the framework of the EU-FP7 project ASTARTE (2013); the installation of new stations is ongoing in both Greece and Italy, funded by the MIUR (Italian Ministry of University and Research) Italian Flagship project RITMARE (Figure 3.21). This is an innovative prospect for the NEAM TWS, given that no operational examples are in place so far in the existing major tsunami warning systems. Of potential innovative interest is also the development of transoceanic submarine cabled observing systems composed of electro-optical seabed cables with optical repeaters for the transmission of data (Howe et al., 2016). Adding environmental sensors to the repeaters would provide an unparalleled global network of real-time data for ocean climate and sea level monitoring and disaster mitigation from earthquake and tsunami hazards.

3.3.2.3 Measuring sea level changes

The measurement of sea-level changes is performed by permanent tide gauge stations installed at coastlines, as well as by ocean buoys, which are floating devices on the sea surface that report the sea level by measuring the pressure on the bottom of the sea. Tide gauges are useful for long-term multihazard purposes and geodynamic and oceanographic studies (e.g. climate change), but they are also useful in tsunami warning if the time interval between the data points and the data latency are sufficiently small.

FIGURE 3.19

Broadband seismic sensors operating in the NEAM region (data retrieved from ORFEUS Data Centre). Different colours indicate different institutions operating sensor networks.
Source: figure prepared by M. Charalampakis, National Observatory of Athens, Greece



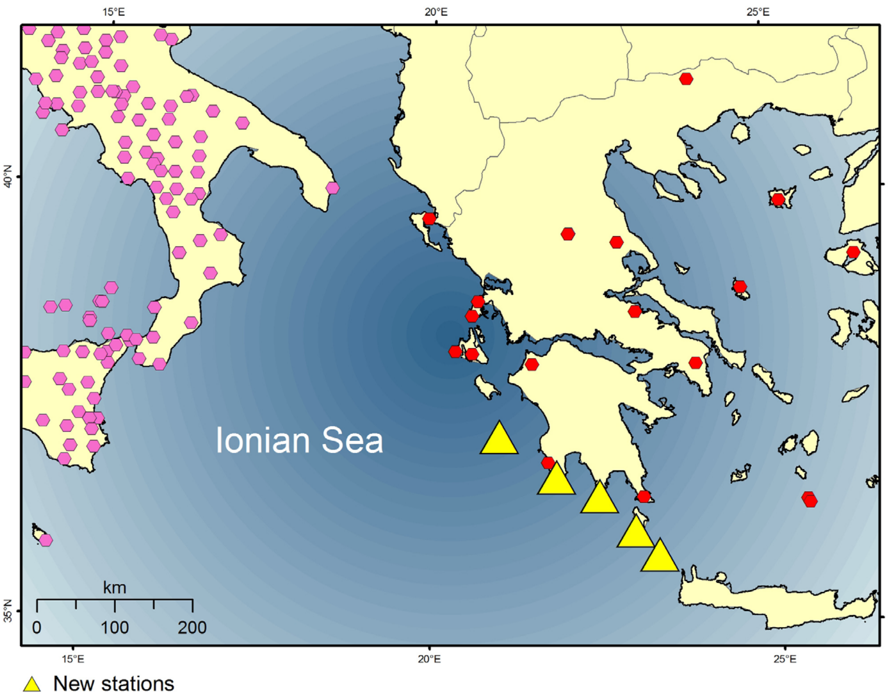
Tide gauges have registered tsunamis since the mid-19th century. For the NEAM region, about 310 stations contribute data to the inventory provided by the Flanders Marine Institute (VLIZ) in Oostende, Belgium, and UNESCO/IOC (2017) (Figure 3.22). However, only a few are available in real time, which is a necessity for early warning. The European Commission (JRC) offers sea-level data redundancy by means of its web service (Webcritech, n.d.). In recent years, JRC has provided more than 20 new Inexpensive Devices for Sea Level (IDSL) measurements in the NEAM region (Annunziato, 2015).

Ocean buoys are linked with pressure sensors on the ocean floor called tsunameters. The pressure change caused by the passage of a tsunami is transmitted to the linked buoy and then to the monitoring centres by satellite. Incorporation of such offshore measurements is desirable to detect a tsunami well in advance of its arrival at the coasts. Measurements of offshore sea levels are achieved by the Deep-Ocean Assessment and Reporting of Tsunami (DART) buoys, which operate in the Pacific, Indian and western Atlantic Oceans. However, there is no clear consensus among the scientific community as regards the suitability of the DART system in more narrow and confined regions such as NEAM, owing not only to their high cost but also to the near-field issue characterising tsunami early warning operations in the NEAM region.

Other types of sea-level measurement include floating GPS systems and the undersea pressure cables, both of which are used operationally by Japan. The first of these measures the sea-level change by the differential measurement with respect to a fixed point on Earth; the second uses a series of pressure measurements that are connected to land stations via submarine cables.

FIGURE 3.20

Map showing stations of the INGV RING (purple dots) and NOANET (red dots) networks. Yellow triangles are the new planned stations, the installation of which has been ongoing since October 2016.
Source: Michelini and Charalampakis (2016).



3.3.3 Tsunami risk assessment and reduction

3.3.3.1 Lessons learned from key tsunami events

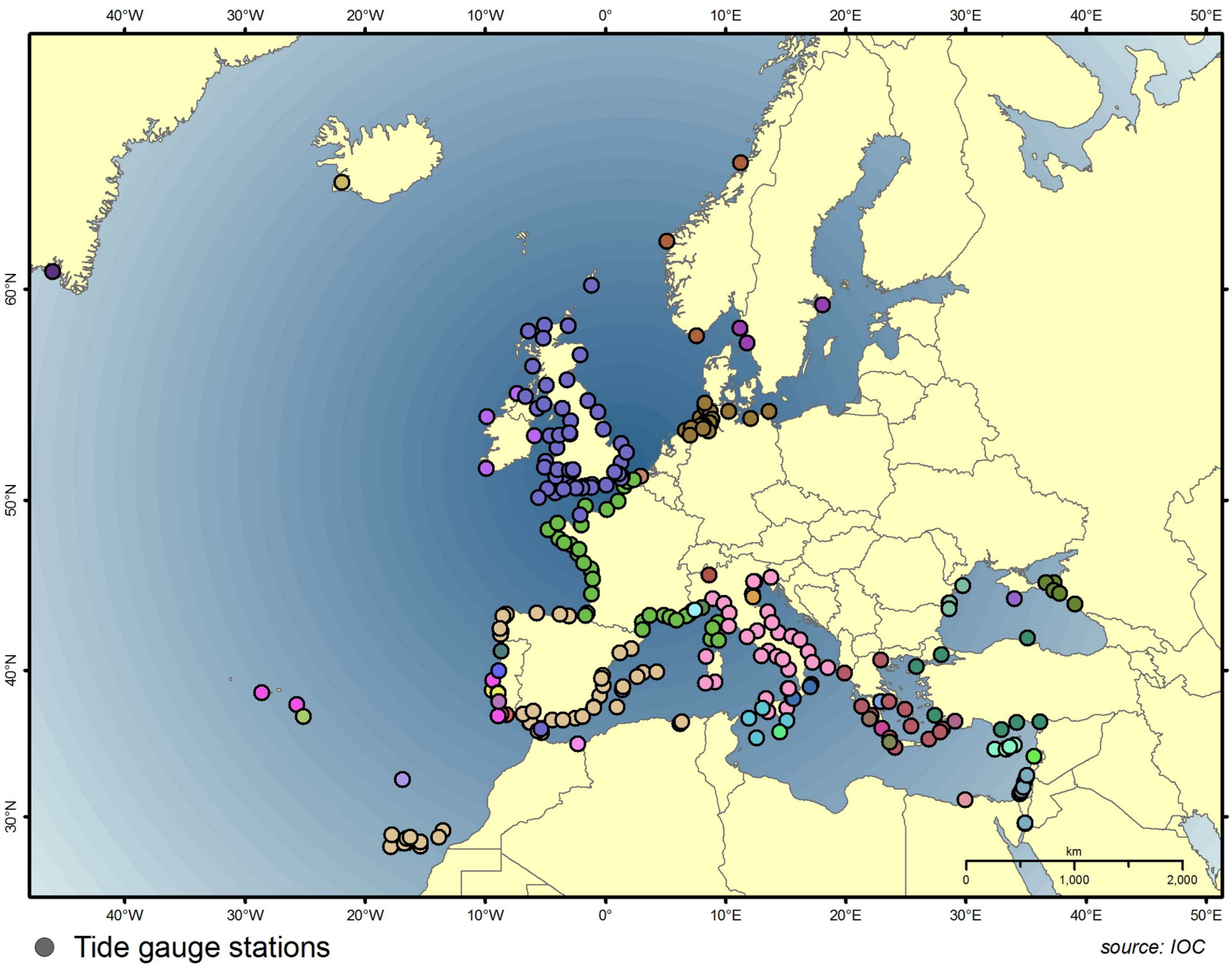
The mega tsunamis of 2004 (Sumatra) and 2011 (Japan) not only had tragic consequences, but also changed our thinking on how to deal with such low-frequency but high-impact events (e.g. Lorito et al., 2016). Both tsunamis led to a reanalysis of previous models for predicting where large earthquakes might recur and how large they might be. At present, we cannot rule out the occurrence of similar megathrust earthquakes along any subduction zone across the Earth, including the Mediterranean Sea (e.g. Kagan and Jackson, 2013). Harsh lessons have also been learned from more localised tsunamis occurring after smaller earthquakes.

The 1998 Papua New Guinea event was an eye-opener for the tsunami community, as it proved that submarine landslides after an earthquake may cause massive tsunamis. The 25 October 2010 Mentawai (off Sumatra) tsunami was caused by an M7.7 'slow' earthquake, which is characterised by a relatively small magnitude compared with the size of the associated tsunami. The shaking from this event was not very strong, but it lasted for a long time. This may be one reason why many people did not self-evacuate, which unfortunately led to more than 400 casualties (Synolakis, 2011). These types of event are termed 'tsunami earthquakes' (Polet and Kanamori, 2009); however, their mechanism is still not completely understood, and the estimation of their frequency and possible locations remains elusive.

3.3.3.2 Tsunami hazard, vulnerability and risk assessment

FIGURE 3.21

Tide gauge stations operating in the NEAM region. Different colours indicate different institutions operating sensor networks.
Source: IOC/UNESCO; figure prepared by M. Charalampakis, NOA, Greece



Tsunami hazard measures the likelihood that a tsunami of a certain size will hit a coastal location in the future, that is, the probability of a tsunami exceeding a run-up height of 10 metres within a period of 50 years. Likewise, building vulnerability describes the probability of tsunami damage and exposure relates to the people, buildings or assets that are subject to potential losses. The tsunami risk measures the probability of future tsunami consequences and any potential losses. In simple terms, the tsunami risk is the convolution between tsunami hazard, vulnerability and exposed elements at risk.

Rare but often destructive events dominate tsunami risk worldwide. Historical tsunami records are too short to reveal run-up heights at the level of hazard for which we need to prepare. This is a fundamental difference between tsunamis and earthquakes, floods or cyclones, for example, for which destructive events can be found in regional historical records and for which the hazard posed by future events can be more robustly extracted from the available data. The considerable uncertainty characterising the assessment of tsunami hazard in most locations needs to be reduced by corroborating, or even replacing, the statistical analysis of past events with the statistical and physics-based modelling of potential future sources, in combination with numerical modelling of tsunami generation, propagation and inundation (e.g. Geist and Parsons, 2006; Burbidge et al., 2008; Power et al., 2013).

Traditionally, the tsunami threat was analysed by modelling the inundation for just a few scenarios, sometimes termed worst-case scenarios. In this way, neither the relative likelihood of events of different sizes (the natural or aleatory uncertainty) nor the degree of belief that one has regarding different plausible but alternative models of the same phenomenon (the epistemic uncertainty) is generally addressed. Moreover, the worst-case approaches are prone to overlook the hazard and risk posed by more frequent, smaller events, which may dominate the risk at certain locations exactly because they are more frequent.

Tsunami risk management requires synergy between the scientific community, decision-makers, civil protection authorities and other stakeholders for hazard, vulnerability and risk assessment, warning systems operation, preparedness, training and emergency planning.

Presently, however, probabilistic tsunami hazard (PTHA) and probabilistic tsunami risk assessments (PTRAs) are progressively replacing the traditional worst-case scenarios methods, which nevertheless remain an important initial screening tool. Probabilistic methods allow systematic analyses to be made of how the sources of uncertainty affect the hazard and risk assessment, which are inherently large for tsunamis. All of this information is vital for any risk-reduction planning measure, including the cost–benefit analysis in comparison with other risks at a given site. PTRA (Løvholt et al., 2015) is already conducted at a global scale for the 2015 UNISDR Global Assessment Report (UNISDR, 2015a). A global analysis of epistemic uncertainty was incorporated in a follow-up global PTHA study (Davies et al., 2016). Previous hazard and risk analyses in the NEAM region have been based mostly on scenario analysis (e.g. Tinti and Armigliato, 2003; Tinti et al., 2005; Lorito et al., 2008; Tonini et al., 2011). More recently, studies dealing with new PTHA methods have been applied in the NEAM region, mostly for earthquake sources (Grezio et al., 2010; Sørensen et al., 2012; Lorito et al., 2015; Omira et al., 2016; Selva et al., 2016). Some risk scenarios have been developed within the EU FP7 ASTARTE project, and approaches to PTRA have also been explored within the EU FP7 STREST project, which deals with natural hazard multirisk assessment for non-nuclear critical infrastructures.

One important ongoing initiative is the TSUMAPS-NEAM project (n.d.), funded by EU budget, which in 2017 will provide the first official community-based and homogeneous regional PTHA for the NEAM region. Recently, probabilistic tsunami hazard maps have been developed on a national scale (e.g. in Italy, Greece, Portugal), which will probably benefit from the existence of the regional assessment. To date, approaches for tsunami risk analysis are not well standardised. To improve the situation, the Global Tsunami Model initiative (n.d.) aims to provide a coordinated response to tsunami hazard and risk assessment worldwide.

This effort has already been endorsed by the Global Facility for Disaster Reduction and Recovery and UNISDR, with the goal of contributing to the implementation of the 2015–30 Sendai framework for disaster risk reduction (UNISDR, 2015b). Although the GTM is not yet fully operational, several GTM partners have been involved in the TSUMAPS-NEAM multiple-expert integration process and review, in an important first step towards standardisation.

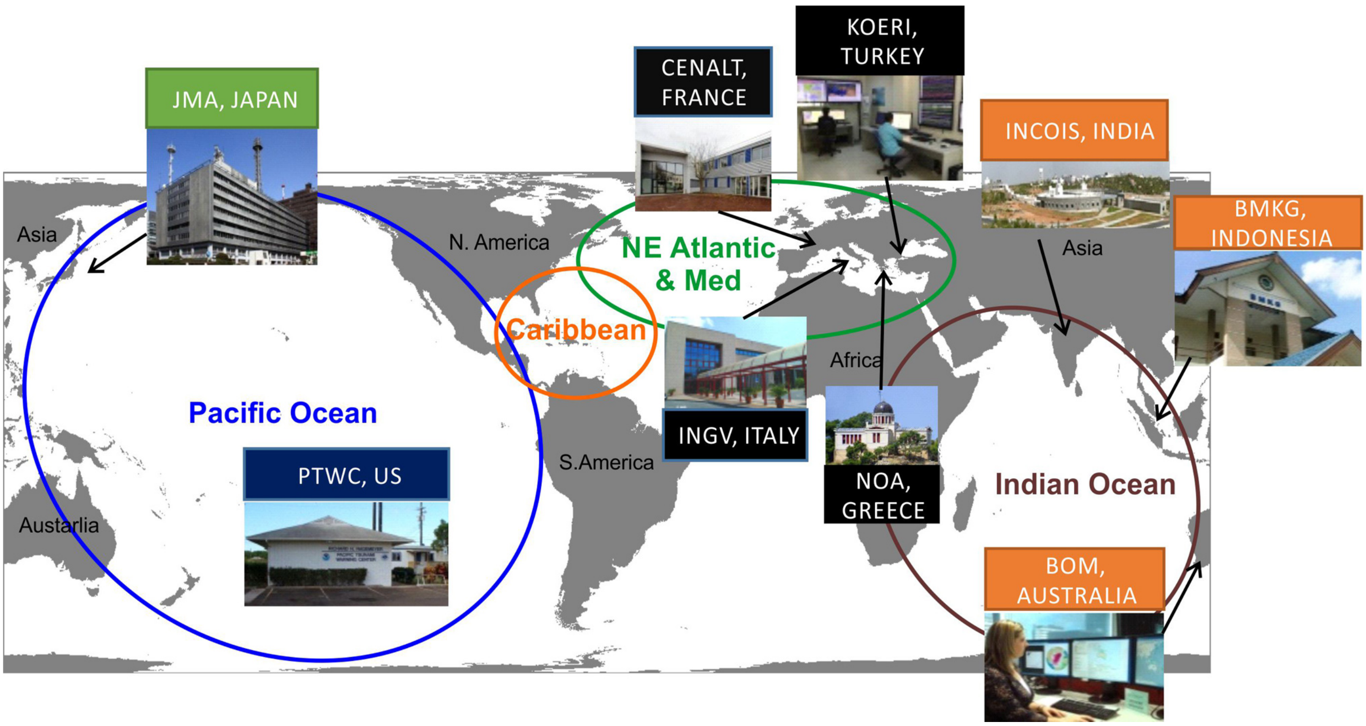
Another difficulty in reliably assessing tsunami risk is that vulnerability is a highly time-dependent parameter, owing not only to changes in the built environment and socioeconomic situations in the long term, but also to temporal variations in exposure (e.g. seasonal and daily variations of population).

3.3.3.3 Early warning systems: a worldwide overview

The objective of a TWS is to identify earthquake tsunami sources, detect tsunamis in advance and issue warnings to communities at risk, to prevent loss of life and to reduce damage. A typical TWS has four main components: risk knowledge, monitoring and warning, dissemination and communication, response capability. A national TWS has operated in Japan since the 1950s. In the Pacific Ocean, a coordinated TWS involving many nations was established in 1965 and has been operating under the IOC/UNESCO umbrella. In the aftermath of the devastating 2004 Sumatra tsunami, the national delegates at the IOC/UNESCO meeting decided to establish three international systems, one in each of the Indian Ocean, Caribbean Sea and the NEAM region. At present, four international systems operate under the IOC umbrella (Figure 3.22). All four systems operate based on National Tsunami Warning Centres (NTWCs) coordinated by

FIGURE 3.22

The four major TWSs operating around the globe under the coordination of IOC/UNESCO and the TSPs already established.
Source: IOC/UNESCO, modified by A. Rudloff, GFZ, Germany



the relevant Intergovernmental Coordination Groups (ICGs). Germany strongly supported efforts to build up a national TWS in Indonesia (Rudloff et al., 2009; Münch et al., 2011).

The identification of earthquake sources is made possible by seismograph networks, while GNSS networks have the potential to achieve the rapid and accurate assessment of magnitude for large earthquakes in the future. Tsunami detection and confirmation is achievable using sea-level records from tide gauges, which are also useful for warning distant places. Many European Member States have invested a lot during the past decade to upgrade their sea-level networks for faster and better tsunami detection, but much remains to be done for an effective warning system. However, offshore instrumentations of the DART type are very expensive in comparison with tide gauge networks. Japan has implemented cable systems that include pressure sensors, seismometers and accelerometers. Such equipment is expensive but lasts more than a decade and has a very low maintenance cost.

Setting up an end-to-end TWS requires partnership and coordination among different national and international institutions and organisations, including those responsible for seismic and sea-level monitoring, civil protection authorities and communities at risk. Moreover, it requires considerable financial investment to support tsunami research, to build, maintain and upgrade comprehensive monitoring networks, and to raise community awareness and preparedness.

There is also a need to develop clear

TABLE 3.1

Decision matrix for the Mediterranean basin, proposed by the ICG/NEAMTWS/IOC/UNESCO system in November 2010. Since then, NTWCs have slightly updated/modified this DM but its main structure remains operational. The DM adopted for the North-East Atlantic is similar.
Source: IOC/UNESCO, elaborated by the authors

Focal depth	Epicentre location	Mw	Tsunami potential	Tsunami message type		
				Local	Regional	Basin
<100km	Offshore or close to the coast (≤40 km inland)	>5.5 and ≤6.0	Weak potential for local tsunami	Advisory	Information	Information
		>6.0 and ≤6.5	Potential for a destructive local tsunami (<100 km)	Watch	Advisory	Information
	Offshore or close to the coast (≤100km inland)	>6.5 and ≤7.0	Potential for a destructive regional tsunami (<400 km)	Watch	Watch	Advisory
		>7.0	Potential for a destructive basin-wide tsunami	Watch	Watch	Watch
≥100km	Offshore or inland ≤100km	>5.5	Nil	Information	Information	Information

legal frameworks for each country, whereby the roles and responsibilities of the institutions and organisations involved will be clearly defined.

3.3.3.4 Tsunami warning systems in the NEAM region: the NEAMTWS/IOC/ UNESCO and JRC/EC initiatives

Since the establishment of the ICG/NEAMTWS/IOC/UNESCO system in 2005, the member countries have worked together to build up the system. Initially the system was based on four NTWCs, which, since the summer of 2012 (France, Greece, Turkey) and spring of 2014 (Italy), have acted as candidate TSPs (CTSPs) for all ICG Member States interested in subscribing to the service. The current average time to issue tsunami warnings is approximately 8-12 minutes. Tsunami messages are also sent to the IOC (Paris), the ERCC (EU, Brussels) and the JRC (Ispra). Following a table-top accreditation procedure by international experts, the CTSPs were successfully evaluated and nominated as TSPs at the 13th ICG Session, Bucharest, September 2016. Since the operational NEAM TWS started (summer 2012), the system was activated in about 25 earthquake events of $M \geq 5.5$. The NTWCs of Portugal and Romania are preparing to start acting as CTSPs soon.

The TSPs are supported in their operations by a decision matrix (DM), namely a simplified and conservative set of empirical rules for the possibility for tsunami generation depending on the earthquake magnitude, epicentre and focal depth (Table 1). The tsunami severity scales with the earthquake magnitude range to produce three tsunami message types: Tsunami Information, Tsunami Advisory, Tsunami Watch. The magnitude range also determines the maximum distance at which a tsunami impact is likely to be caused at coastlines. Therefore, local (≤ 100 km), regional (≤400 km) and basin-wide tsunami message types are considered. Tsunami arrival times in pre-defined coastal forecast points are calculated and inserted in the alert message. Next, sea-level data analysis is undertaken to monitor and confirm the tsunami by issuing ongoing alert messages or to cancel the message if no tsunami is detected. The above procedure underlines the importance of seismograph and tide gauge networks in tsunami warning operations.

Regular communication tests among TSPs and continuous staff training are of utmost importance given that tsunamis are infrequent events. A good example was the Global Tsunami Informal Monitoring Service (2013-16), coordinated by the JRC. Several national TWSs of the NEAM region participated. After a strong ($M \geq 7$), potentially tsunamigenic, earthquake, the TWSs staff initiated a monitoring procedure for the collection of tsunami-related information and records (e.g. in tide gauges) and reported this to the JRC.

Tsunami Service Provider operations might be of great importance not only for early warning, but also for prompt scientific advice on post-disaster management in a multihazard context. The ongoing pilot project ARISTOTLE, funded from budget of

FIGURE 3.23

Tsunami evacuation building in Japan
Source: photograph courtesy of G.A. Papadopoulos

European Union, is providing scientific support not only on tsunamis but also on other types of natural hazards, including earthquakes, volcanic activity and meteorological hazards, to ERCC in the period 2016-17.

3.3.3.5 Preparedness-Education-Training and the role of Civil Protection

The mitigation of tsunami risk should rely not only on early warning but also on the synergy of several actions, including preparedness and emergency planning, exercises, training, education and public awareness. For such activities, the civil protection and other national authorities have a key role to play in order to make the downstream component of the TWS effective down to its 'last mile'.

A key preparedness element is the designation of 'hazard zones' along tsunami-prone coastal segments, which entails an inherently political cost–benefit assessment, relying on the input scientific information provided through hazard and risk assessment. Hazard zones are necessary for long-term risk management actions, including urban and emergency planning. Evacuation during the early warning stage is facilitated by the existence of hazard zones, since everybody needs to know beforehand the area that should be evacuated. Designation of appropriate evacuation buildings is also important for vertical evacuation (Figure 3.23).

Inaccurate hazard assessment may result in an underestimation of the hazard zone, which can have tragic consequences. Japanese tsunami hazard maps prior to 2011 were based on historical earthquake records with upper bound earthquake moment magnitudes that were too small (Geller, 2011). This is probably reflected in the (ex post) insufficiently cautionary risk management of the Fukushima nuclear power plant (Synolakis and Kanoglu, 2015). In some coastal areas, evacuees felt sufficiently safe to move just outside the hazard zone limits. However, the 2011 tsunami proved larger than the 'design tsunami' and killed many people outside the hazard zones.

Awareness and preparedness may be enhanced by table-top drills based on tsunami scenarios, such as the NEAMWAVE12 (2012) and NEAMWAVE14 (2014), which involved TSPs, civil protection authorities and the ERCC. Operational exercises also offer a good basis on which to test and improve emergency plans and rescue capabilities (e.g. POSEIDON-2012, supported by EU budget, was an exercise performed on Crete, Greece). Education and public awareness are very important, since their aim is to teach people about tsunami risk and ways to reduce it.

3.3.4 Conclusions and key messages

Tsunamis are caused mainly by submarine earthquakes but also by landslides, volcanic eruptions or other causes. Complex cascading effects involving more than one tsunami generation mechanism should not ignored (e.g. tsunamis caused by landslides that are triggered by earthquakes).

Tsunamis are characterised as low-probability but high-impact events. While they are most frequent in the Pacific, the tsunami hazard is also present in the Indian Ocean, the NEAM region, the Caribbean Sea and elsewhere. The assessment of tsunami hazard and risk is susceptible to a variety of uncertainties, including our limited knowledge of the likelihood of infrequent tsunami sources, or the complexity of the tsunami inundation.

Partnership

The assessment of the impact incorporates many fields of physical sciences, hazard modelling, engineering and social sciences. Neglecting any of these fields will inevitably reduce the accuracy, reliability and usefulness of the resulting risk metrics. The process of risk identification should involve stakeholders from the public and private sectors and should leverage ongoing national and international initiatives with the mandate to calculate, communicate and reduce geophysical risks.

Even the most advanced TWS is not effective without a well-trained downstream component. Tsunami risk mitigation thus requires synergies between the scientific and technological communities, decision-makers, civil protection authorities and other stakeholders. The common aim should be continual exercise and training, education and public awareness; this is vital, since the public perception of the risk from infrequent events naturally tends to fade over time, until the next catastrophe happens.

Knowledge

A thorough understanding of tsunami hazard and risk should not be based solely on the analysis of past events, but must exploit broader scientific analysis and modelling in order to assess the potential for future hazards. Exposure and vulnerability (e.g. of populations) are time-dependent parameters, which makes risk assessment a complex procedure. Standards and best practices for tsunami hazard and risk assessment need to be further established by the international community, in order to better support preparedness and emergency planning.

Innovation

The experiences of the past 20 years or so leave no doubt that TWSs that are well suited to the rapid detection of large magnitude earthquakes are necessary. Well-developed instrumental networks of seismographs, tide gauges and tsunameters substantially support TWSs. However, major gaps still exist in the coverage of large areas (e.g. North Africa). The present TWS performance could be improved by filling in network gaps. An important issue, however, is the constant TWS maintenance, which requires regular funding and technical support.

Technological innovations that may drastically improve TWS performance include the utilisation of GNSS networks for rapid and accurate large earthquake magnitude calculation. Of innovative value is the utilisation of submarine cable systems for the transmission of seismic, tsunami and other signals recorded on the sea floor for multihazard purposes, including seismic, volcanic and tsunami early warning, climate monitoring and other future societal needs. Satellite data (e.g. buildings, road networks) will become more and more valuable for risk assessment.

Civil protection authorities should elaborate plans to determine coastal hazard zones as well as to ensure that tsunami warnings arrive on time to local authorities and the general public. In parallel, best practices for evacuation procedures should be elaborated and communicated to the public. These are issues of critical importance given that many tsunami sources in the NEAM and beyond are located in the near-field domain; thus, coastal populations are threatened by the fact that any tsunami could reach the coastline in less than 30 minutes.

Recommendations

Earthquakes, volcanic eruptions and tsunamis are characterised as low-probability but high-consequence events. The assessment of the impact of such catastrophic events incorporates many fields of physical sciences, hazard modelling, engineering and social sciences. Neglecting any of these fields will inevitably reduce the accuracy, reliability and usefulness of the resulting risk metrics. The process of risk identification should involve stakeholders from the public and private sectors and should leverage ongoing national and international initiatives with the mandate to calculate, communicate and reduce geophysical risks.

In the past two decades or so, the European Commission has supported a large number of projects that have significantly advanced the science of earthquake, volcanic and tsunami hazard modelling and risk assessment. Other national and international programmes have also produced datasets, models and tools that are fundamental for the assessment of geophysical risks. Leveraging on this wealth of resources will reduce the replication of efforts. It is also important that the international community investigates efficient approaches to, and develops standards and best practices for, hazard and risk assessment based on existing risk knowledge to enable effective DRM, including preparedness and emergency planning.

Existing instrumental networks support EWSs mainly for earthquakes and tsunamis and, to a lesser degree, volcanic eruptions. However, major gaps still exist in the instrumental coverage of large areas. The present performance of TWSs for the protection of populations should be improved by filling the gaps in these networks. However, even the most advanced EWSs are not effective without a well-trained downstream component. Geophysical risk mitigation thus requires synergies between the scientific and technological community, civil protection authorities and other stakeholders. The common aim should be continual exercises and training, education and public awareness; this is vital, since the public perception of risk from infrequent events naturally tends to fade over time, until the next catastrophe happens.

Geophysical risk assessment is fundamental to incorporate the wide spectrum of uncertainties from the different risk components (hazard, exposure and vulnerability). Satellite imagery and VGI are enabling the characterisation of the built environment with unprecedented temporal and spatial detail. Moreover, the development of risk-reduction strategies not only should rely on the direct (or physical) impact, but should also incorporate socioeconomic aspects, thus considering the capability of the society to recover from destructive events.

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Chapter 3

Understanding disaster risk: hazard related risk issues

SECTION II
Hydrological risk

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3 Understanding disaster risk: hazard related risk issues

Section II. Hydrological risk

CONTENTS

Introduction

The following subchapters cover the principal hydrological risks and, in the case of landslides, hazards that are triggered through hydrological events. In the case of floods, the subchapters cover fluvial, flash and pluvial floods, as well as coastal flooding caused by wave actions and storm surges:

- Fluvial floods occur when river levels rise and burst or overflow their banks, inundating the surrounding land forming the river's floodplain. This can occur in response to storms with higher than normal rainfall totals and/or intensities, to seasonal strong weather systems such as monsoons or winter stormtracks, or to sudden melting of snow in spring.

- Flash floods can develop when heavy rainfall occurs suddenly, particularly in mountainous river catchments, although they can occur anywhere. Strong localised rainfall, rapid flood formation and high water velocities can be particularly threatening to the population at risk and are highly destructive.

- Heavy rainfall may cause surface water flooding, also known as pluvial flooding, particularly in cities where the urban drainage systems become overwhelmed.

- Floods can also be generated by infrastructure failure (e.g. dam breaks), glacial/lake outbursts and groundwater rising under prolonged very wet conditions, which cause waterlogging. In many cases, flooding occurs as a result of more than one of the generating mechanisms occurring concurrently, making the prediction of flood hazards and impacts even more challenging, and the probable resulting damage more severe.

- Coastal flooding is caused by a combination of high tide, storm surge and wave conditions. Development on flood plains increases the risk as does coastal erosion and sea level rise.

- Landslide occurrence is related to causal factors, which create a propensity for a slope to fail and trigger the specific external event that induces landslide occurrence at that particular time. In most cases, but not all, the timing of failure is associated with a trigger event.

- Heavy rainfall is a key factor in generating landslides, primarily through the generation of pore water pressures and a reduction in the effective normal stress. The second key factor for landslide generation is the impact of seismic events.

Floods and landslides affect a large number of people across the world every year, with severe socioeconomic impacts. Severe fluvial flooding repeatedly afflicts European populations, with trans-national events often being the most damaging. It is estimated that GBP 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding in the United Kingdom alone, for example. Significant advances have been made in recent years to map these risks, to develop and set up EWSs for better preparedness and to improve the communication of risks to decision-makers and the public. However, variations in socioeconomic factors (land use, demography, migration) as well as changes in climate and weather patterns may lead to rapid changes in flood and landslide risk in the future and will require increased levels of adaptation.

This chapter describes the current knowledge regarding the drivers, impacts and key tools to manage risks for these hazards. It identifies a set of challenges and gaps for key stakeholders to further reduce and better manage their risks and to be prepared for future changes in risk.

3.4 Hydrological risk: floods

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3.4.1 Introduction: flood hazards and impacts

In principle, flooding is a natural phenomenon that affects all river basins around the world in more or less regular intervals and that fulfils essential functions in the natural ecosystem. However, owing to human settlements being established within floodplains and common development practices not leaving room for rivers under flood conditions, flooding is mostly considered for its negative rather than its positive effects (Watson and Adams, 2010). Alfieri et al. (2016) estimate flood impact at the European Union level to be ≈EUR 6 billion per year, affecting 250 000 people per year. Although flood impact assessment is an essential step by which to optimise flood mitigation measures, there are many sources of uncertainty that affect such complex estimates. For example, uncertainty may come from sparse and short datasets, poor knowledge of hydraulic structures such as dams and weirs along rivers, assumptions and extrapolations in statistical analyses of extreme floods, and depth-damage functions. The estimation of flood damages also depends on several assumptions (Merz et al., 2010). It involves challenges in defining damages for different elements at risk (e.g. houses, public spaces, industries), and transferring solutions in space (from one region to another) and in time (from one flood event to another).

Flooding causes long-term damage to health, with immediate impacts such as drowning, physical trauma, infections and chemical hazards, and also affects well-being, livelihoods and social cohesion. It is also not always easy to identify the local consequences of flooding, such as the effects caused by displacement, the destruction of homes, delayed recovery and the disruption of access to health services (WHO, 2013). Flooding can also cause damage to critical infrastructure and can interrupt health and social care service delivery and business supply chains (National Flood Resilience Review, 2016; Landeg and Lawson, 2014). Finally, flooding is also frequently associated with power outages, which themselves can have a detrimental impact on health and businesses (Klinger et al., 2014) and a knock-on effect on other critical infrastructure such as railways and wastewater services.

Flood disasters affect a large number of people across the world every year, with severe social and economic impacts. Severe flooding repeatedly affects European populations, with trans-national events often being the most damaging.

The vulnerability of riverside communities around the world is particularly worrying in the light of migration pressures, socioeconomic drivers and climatic change. Even those who live flood-adapted lifestyles are not resilient to severe floods that occur only rarely, particularly when the last big flood was beyond living memory (Garde-Hansen et al., 2016) and in light of the impacts of future climate change.

In this subchapter, the main drivers of flood hazard are introduced and flood hazard and risk mapping are discussed, particularly at the regional scale. Flood predictability is then considered, along with a review of the added value of flood monitoring, flood forecasting and EWSs.

3.4.2 Living with floods

Learning to live with flooding means that we recognise that flooding will continue to happen, as it is a natural phenomenon. There are many uncertainties in knowing when and where a flood will happen, both in the immediate term and in terms of probable climate change timescales, and when it does flood there is inevitably some disruption to our lives. However, there are many things that we can do to prepare better for floods and manage the risk, including strengthening components of flood prevention, flood preparedness, flood response and flood recovery, which are part of the disaster cycle (Figure 3.). Interventions can be taken during a flood to limit the impact of the disaster, including the evacuation of settlements or the creation of additional flood relief space through the opening of dykes or dams. This response is followed by a recovery phase after the disaster has passed, which includes relief meas-

FIGURE 3.24

Hazards and risk event cycle
Source: courtesy of authors

ures, reconstruction and event analysis. Often, this phase is aligned with the aim to achieve a similar economic standard to that before the event.

Our best strategy for flood management is learning to live with flooding, that is, preparing ourselves today to be better adapted for flood risks tomorrow. The combination of a strong flood risk management policy, advanced early warning technology and increased international collaboration have the potential to reduce flood risk and improve disaster response from the local to the global scale. This requires different disciplines of knowledge, scientists, policymakers and practitioners to work closely together.

If society has learned from the event, then any recovery is followed by a disaster risk-reduction phase, which includes preventive measures (e.g. creating natural retention in catchments, changing land use, rethinking urban design, planning and architectural norms, and implementing structural flood defences) and precautionary measures (e.g. supporting insurance mechanisms, refitting buildings, training and using EWSs). The aim is to minimise the vulnerability of society and to prepare it for an adequate response and recovery after the next event. The diversity in the way societies prepare for, respond to and recover from floods is largely governed by their experience with flood risk management and the magnitude of the floods that they have historically experienced (Thieken et al., 2007).

Improving flood preparedness requires contributions from many different disciplines of knowledge. Efforts are needed in terms of (1) improving risk governance, including institutional governance, legal provisions and financial instruments for planning, prevention and crises management, (2) understanding hazard modelling, incorporating meteorological forcing, hydrological, river and urban drainage processes, (3) forecasts and predictions, from short to long lead time ranges, and (4) emergency response recovery, including coordination of local operations, assistance to affected communities and recovery of disrupted services. Communication with and engagement of the public, water managers and decision-makers is key to effectively integrate these layers and to improve flood preparedness.

3.4.3 Drivers of flood hazard

Floods happen for a variety of reasons, but the main drivers are usually related to high rainfall, snowmelt and high river flow conditions (see Chapter 3.6). Fluvial floods occur when river levels rise and burst or overflow their banks, inundating the surrounding land that forms the river's floodplain. This can occur in response to storms with higher than normal rainfall totals and/or intensities, seasonal strong weather systems such as monsoons or winter stormtracks, or the sudden melting of snow in spring. The spring 2006 flood in the upper part of Elbe river basin is an example of a flood event driven by snowmelt combined with precipitation (Younis et al., 2008). With the rapid increase in temperature in April, snow that was present in the catchment was completely melted in 7-14 days. While temperature is generally easier to forecast than precipitation, the assessment of the quantities of snow accumulated in the catchment during the winter season can be a challenge for many EWSs.

Floods can be triggered by rivers bursting or overflowing their banks, storm surges in the ocean, tsunamis, groundwater rising, glacial outbursts or dam failures and from surface water runoff in our cities after heavy rain.

The severity of fluvial floods can be enhanced when the landscape is already saturated with water. Runoff due to rainfall cannot infiltrate the ground and, instead, flows directly to the river channel, rapidly contributing to increased river levels. This occurred in the winter 2013/14 floods in the south of the United Kingdom, where an unusual series of storms led to widespread flooding (Huntingford et al., 2014; Muchan et al., 2015), and in the 2013 floods in Germany (Schröter et al., 2015).

Flash floods can develop when heavy rainfall occurs suddenly, particularly in mountainous river catchments, although they can occur anywhere (Gaume et al., 2009; Brauer et al., 2011). In flash floods, the rate at which river water levels rise is very rapid and the flood forms quickly. High levels of localised rainfall, rapid flood formation and high water velocities can be particularly threatening to the population at risk and highly destructive. Challenges in the management of flash floods include the short preparation time to activate flood alerts and emergency response, the sudden nature of the phenomenon, which often catches the population at risk by surprise, the difficulties of numerical weather prediction models in forecasting localised convective storms, and the lack of quantitative data at small catchment level to improve the understanding and modelling of flash floods (Collier, 2007; Leichti et al., 2013; Alfieri et al., 2011).

Heavy rainfall may cause surface water flooding, also known as pluvial flooding, particularly in cities where the urban drainage systems become overwhelmed. In these cases, event monitoring from telemetric rain gauges or meteorological radar needs to be coupled with hydrological, hydraulic and drainage system models for flood mapping (Liguori et al., 2012). Challenges remain with regard to estimating accurately rainfall displacement over an urban area, as well as with regard to precise knowledge of the capacity of the sewer system as a result of, for instance, debris blockages, infrastructure failure (broken or cracked pipes) or a reduction of pluvial capacity (Chen et al., 2016).

Floods can also be generated by infrastructure failure (e.g. dam breaks), glacial/lake outbursts, storm surges and wave overtopping at the coast (see Chapter 3.6), and groundwater rising under very wet prolonged conditions, thereby causing waterlogging (Macdonald et al., 2012). In many cases, flooding occurs when more than one of the generating mechanisms happen concurrently, making the prediction of flood hazards and impacts even more challenging, and the probable resulting damage more severe. In addition, longer-term drivers of flood impacts are also of concern in many vulnerable areas. They include changes in land use, population and geomorphology and the impacts of a changing climate (Alfieri et al., 2015; Slater et al., 2015). These issues are not straightforward to determine because of the many uncertainties involved in using climate and socioeconomic models to drive flood hazard predictions and the difficulties in their evaluation (Cloke et al., 2013; Hall et al., 2014; Hirabayashi et al., 2013; Kendon et al., 2016; Vormoor et al., 2015).

3.4.4 Flood hazard and risk mapping

Flood risk can be calculated from the hydrological flood hazard by including information on the exposure and vulnerability of populations and assets. They are needed at different spatial scales, from local and national to global scales, and at different temporal scales, from upcoming days to decades. Flood risk management measures are key to flood hazard and risk mapping. Flood risk management is considered at the European level by the Floods Directive 2007/60/EC (European Commission, 2007) which directs EU Member states to adequately assess and manage their flood risk. This involves mapping the flood hazard extent, assessing the flood risk and producing flood risk management plans, which also consider the longer-term drivers of land use and climate change.

Flood hazard can be calculated by assessing the probability of any particular area being flooded. Usually, it is undertaken with respect to a particular level of flood, for example, the 0.01 Annual Exceedance Probability threshold (also commonly known as the '100-year flood' with a return period of 100 years, which is better understood as a flood that has a 1 % probability of occurring at any given location in any given year). Flood risk takes the flood hazard and combines this with information on the potential damage to society, such as vulnerability and the exposure of assets and populations in the floodplain. Approaches can be different depending on the temporal and spatial scales at which the flood hazard and risk assessment are applied, on the modelling tools and data available and on the type of flood hazard (e.g. if it is a fluvial, surface water or coastal flood).

A fully comprehensive flood risk map requires a great number of data, a series of floods events over a long period and a chain of models and assessments (Sampson et al., 2014, Dottori et al., 2016), although simpler mapping based solely on flood events or other historical information can also be useful (Boudou et al., 2015).

Flood hazard and flood risk maps are required for land use planning, floodplain management, disaster response planning and financial risk planning. They can be produced at increasingly higher resolutions using flood modelling tools. Uncertainties can be taken into account by using probabilistic methods. A focus on flood hazard impacts can enhance communication to the public.

For fluvial floods, a full risk mapping requires long-term series of hydrometeorological data, satellite data on the flood extent for the assimilation of spatial information, large datasets on population/asset exposure and flood protection standards (Scussolini et al., 2016), and commercially sensitive damage data from insurance companies, which are often not openly accessible. Longer timescale changes in flood risk are usually assessed through scenarios of climate change and socioeconomic development (Apel et al., 2008; Winsemius et al., 2013). These can take into account flood policies, such as the implementation of flood protection measures, as well as the interaction of human and physical systems, such as the adaptation effect and the failed levee effect (Di Baldassare et al., 2015; Collenteur et al., 2015).

Flood hazard maps can be produced by using hydraulic models to simulate water flow along rivers, over floodplains and in urban surface water accumulation zones. Simulations are often combined with Geographic Information System (GIS) techniques to build flood maps. This ideally requires substantial observed data for model calibration and validation. For fluvial floods, hydraulic models can use time series of historical river flows, historical rainfalls or time series of synthetic design rainfall events, in conjunction with catchment hydrology rainfall-runoff models. However, even the most sophisticated approaches have difficulty producing robust estimates of extreme events (Sampson et al., 2014), which can be problematic if these maps are the only resources used to support decision-making processes, such as urban planning. Describing flood inundation hazard and risk using probabilistic methods is therefore encouraged (Romanowicz and Beven, 2003; Pappenberger et al., 2006). For example, flood inundation hazard can be mapped from the development and set-up of flood inundation models, a sensitivity analysis using observations, the use of the multiple acceptable ('behavioural') model parameter sets to perform 'ensemble' (multiple) simulations using an uncertain synthetic design event, or an ensemble of scenarios, as input to the flood inundation models (Di Baldassarre et al., 2010). Probabilistic methods can be used, as they assume that, whichever model is chosen, it will not perfectly represent all flood propagation and inundation processes involved. This can be very important when modelling flood inundation in changing environments, when they are subject either to strong land use changes or to climate changes.

Regional-scale fluvial flood hazard mapping has been improved by the use of satellite data assimilation and flood models to map flood inundation pathways. Global flood hazard maps can also be useful in the assessment of flood risk in a number of different applications, including (re) insurance and large-scale flood preparedness. These maps can be created using large-scale computer models of rainfall-runoff processes in river catchments and river routing. They may, however, require the use of a variety of post-processing methods to better adjust simulations to local measurements (Pappenberger et al., 2012; Ward et al., 2013; Winsemius et al., 2013; Dottori et al., 2016). At the local scale, surface water flood hazard mapping (pluvial flooding) has benefited from recent improvements to fine-scale surface water modelling, particularly in cities, on 1-metre or 2-metre grids, integrating topography, land use, urban structures and potentially also subterranean drainage and flooding impacts (Tyrna et al., 2016; Palla et al., 2016).

All numerically produced flood hazard maps, regardless of their spatial scale, require validation in order to be useful. This can be very challenging because of a lack of robust observed data. On local, regional or national scales, validation can be undertaken, at least to some extent, on the basis of past observations of inundation extents, from satellite, ground-based observations or community-based data sources, as well as from river stage and discharge measurements from river gauges. In contrast, the accuracy of global maps is far more challenging, as globally consistent observations can rarely be obtained. Trigg et al. (2016), for instance, describe several different global flood hazard maps, which have been individually validated within a limited context. The estimates of global flood hazard obtained are compared to analyse their consistency and to provide an estimate of model uncertainty. In Africa, the agreement between the different models is relatively low (30-40 %), with major differences in magnitude and spatial extent particularly observed for deltas, arid/semi-arid zones and wetlands, which are all areas that suffer from a lack of data for validation. Such discrepancies can have significant impact: for example, the models showed a large discrepancy in the Nile delta, where approximately 95 % of the population of Egypt lives. This highlights the fact that any global flood hazard map should be used with caution and that multimodel products may be useful (Trigg et al., 2016). The role of databases and post-event analyses is key to improve our understanding of global flood hazard and risk (de Moel et al., 2015).

3.4.5 Flood monitoring, forecasting and early warning systems

The predictability of hydrological systems varies because of the large number of non-linearities in these systems, the challenges in the observability of the state of the hydrological variables, the presence of outliers (rare occurrences), the variability of external forcing and the numerous interactions among processes across scales (Bloschl and Zehe, 2005; Kumar et al., 2011; Peña et al., 2015; Lavers et al., 2011). Different types of floods are predictable with different time ranges. Flash floods driven by convective rainfall are notoriously challenging to predict ahead in time to produce effective early warnings (Collier, 2007; Berenguer et al., 2005), whereas slower developing floods in large catchments can be predicted several days ahead of time with the use of probabilistic flood forecasting systems (Emerton et al., 2016). The use of satellites and EWSs based on computer-intensive forecasts has recently enabled distinct improvements in our ability to provide effective information on the likelihood and severity of upcoming flooding and the extent of the affected area (Alfieri et al., 2013; Revilla-Romero et al., 2015). This information can be provided to agencies, responders, stakeholders and the public in various forms, including interactive watch or warning maps and flood guidance statements (e.g. FFC, n.d.; Vigicrues, 2017).

However, there is substantial uncertainty in predicting floods, which stems from the uncertainty in the atmosphere, the complexity of the land-surface processes and the imperfection in the computer models used to represent them (Cloke and Pappenberger, 2009; Rodríguez-Rincón et al., 2015). Ensemble techniques can be used to represent the main sources of predictive uncertainty. These use multiple simulations based on different model set-ups, model parameters, initial conditions, data, etc. Rather than just providing one 'best guess' prediction, ensembles provide a whole range of model realisations and equally possible predictions for the future. Information can be obtained on which scenarios are most likely to happen and on the worst possible scenario (given our current knowledge of initial conditions and process representation). This can be useful to communicate forecast uncertainty and to help stakeholders to take more informed decisions (Cloke and Pappenberger, 2009; Stephens and Cloke, 2014; Zsótér et al., 2016). The HEPEX initiative (Hydrologic Ensemble Prediction Experiment, n.d.) seeks to advance the science and practice of hydrologic ensemble prediction and its use in risk-based decision-making by engaging researchers, forecasts and users in several community activities.

Real-time monitoring and rapid mapping of floods based on satellite data have been implemented at a variety of scales and by a number of different actors to detect flooding severity and extent in affected areas. For instance, the Copernicus Emergency Management Service—Mapping (2017) integrates satellite remote sensing and available in situ data to provide stakeholders with timely and accurate geospatial information in emergency situations and humanitarian crises (not just for floods, but also other hazards). It operates for the full emergency management cycle and can be broadly divided into (1) a Rapid Mapping component, which provides on-demand information within hours or days, usually immediately in response to a disaster event, and (2) a risk and recovery mapping to support activities in the area of prevention, preparedness and disaster risk reduction. Another activity in the area of monitoring flooding from space and their impacts is the Dartmouth Flood Observatory (n.d.). Maps are published to provide an overview of flooding impact and extent, and a day-to-day record of flooding occurrences is built for analyses at a later stage. The use of space-based information facilitates international flood detection, response, future risk assessment, and community-wide hydrological research. Improvements in rainfall data assimilation to meteorological models (e.g. Ballard et al., 2016) and soil moisture, discharge and water level data or flood inundation characteristics to flood models (e.g. Garcia-Pintado et al., 2015; Alvarez-Garreton et al., 2015) have also provided improvements in flood forecasting and hazard mapping. Many other vital data have emerged, derived from ground-based imagery flood monitoring, crowdsourcing, unmanned aerial vehicles, rapid flood mapping and post-event data collection by authorities, researchers and local communities (e.g. Walker et al., 2016; Le Coz et al., 2016; Perks et al., 2016).

Numerical weather prediction models have now improved to the point that operational centres can set up hydrometeorological systems that are able to forecast river flow and flooding on larger catchments several days, and even weeks, ahead of an upcoming flood event at global scales (Emerton et al., 2016). Transnational forecasting and warning systems can be of particular benefit, as they provide consistent and comparable information for rivers that cross national boundaries. They can also be useful as support information for all nations that do not have adequate flood forecasting and warning capabilities (Alfieri et al., 2012; Thiemig et al., 2015). As Emerton et al. (2016) argue:

Flood forecasting and EWSs are identified as key preparedness actions for flood risk management and can be implemented at local scales through to continental and global scales. Radar and numerical weather forecasting systems can be used as inputs to flood forecasts, but uncertainties should be taken into account using ensemble (probabilistic) forecasting techniques.

Operational systems currently have the capability to produce coarse-scale discharge forecasts in the medium-range and disseminate forecasts and, in some cases, early warning products in real time across the globe, in support of national forecasting capabilities. With improvements in seasonal weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multi-model forecasts and grand ensemble techniques, responding to the requirement of developing multi-hazard EWSs for disaster risk reduction. Flood magnitude and return period (or average frequency of occurrence) can be assessed for single points on a river. However, for those applications that require a measure of flood severity across an entire region, or 'floodiness', as, for example, in the case of initiating and forecasting the need for humanitarian actions, floodiness indices can be used to provide a spatial view of the risk of flooding (Stephens et al., 2015). Although several applications still rely on rainfall forecasts as a proxy for imminent flood hazard, Stephens et al. (op. cit.) have shown that monthly floodiness is not well correlated with precipitation, which demonstrates the need for hydrometeorological EWSs at such scales.

3.4.6 Copernicus Emergency Management Service: floods (EFAS and GloFAS)

The European Flood Awareness System (EFAS, 2016; operational since 2012) and GloFAS (GloFAS, 2017; due to become operational in early 2017) aim to provide early flood information to national authorities to support national capabilities, particularly with earlier and probabilistic information. EFAS additionally provides information to the European Commission's ERCC to support flood disaster response.

The EFAS project was initiated following the severe 2002 flooding that took place across Europe and has since been enhanced with research developments and user feedback. Large-scale systems not only save lives by increasing flood preparedness, but also have a significant economic benefit. Pappenberger et al. (2015) provide evidence of the monetary benefit in cross-border continental-scale flood EWSs. The potential monetary benefit of EFAS was estimated by combining warning information with existing flood damage cost information and calculations of potential avoided flood damages. The benefits were estimated to be of the order of EUR 400 for every euro invested (Pappenberger et al., 2015).

The benefits of an EWS can also be demonstrated in individual cases of flood warning. For example, EFAS proved to be useful in the widespread flooding that occurred in the Balkans region in south-eastern Europe in 2014. Weeks of continuous rain, combined with an exceptional storm on 13 May, led to heavy flooding in Bosnia-Herzegovina and Serbia, but also in Slovakia, southern Poland and the Czech Republic. The impact

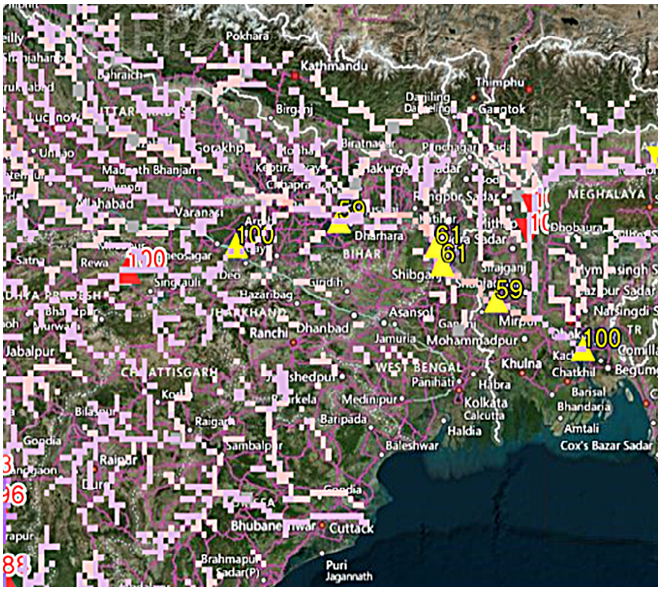
FIGURE 3.25

GloFAS forecasts of the River Ganges floods in July/August 2016.

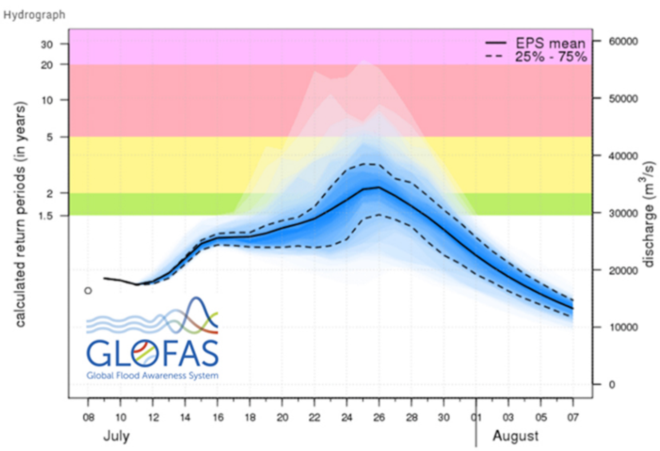
a) forecast map showing river pixels with upcoming floods;
b) forecast ensemble hydrograph for the Ganges at Begusarai (Bihar) on 8 July 2016; 1 week before the flooding started and 18 days before the peak;
c) forecast ensemble hydrography on 21 July 2016, showing the flood peak on 27 July with 98% probability of exceeding the severe alert threshold (20 year return period) and 50% probability of exceeding the 50-year return period.
The colours of the triangles and pixels in (a) and shading in (b,c) are: purple represents severe alert of ≥ 20 year return period; red, high alert of ≥ 5 year return period; yellow, medium alert of ≥ 2 year return period.

Source: GloFAS (2017)

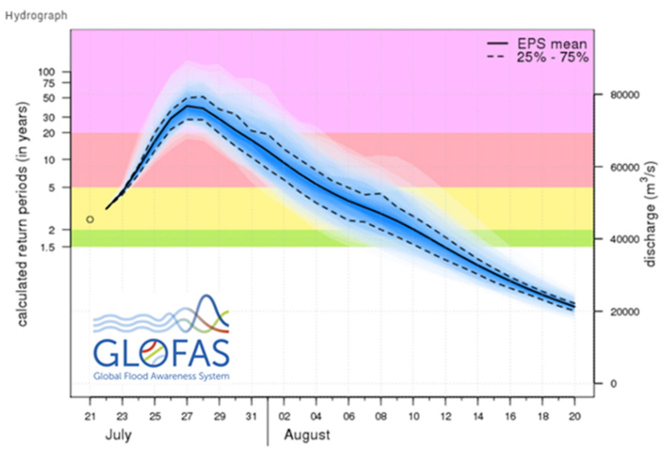
a)



b)



c)



of flooding was so severe that Bosnia-Herzegovina and Serbia requested assistance from the European Union through the EU Community Civil Protection Mechanism. EFAS provided early warnings from 11 May onwards and notified national authorities and the ERCC operating within the Commission's Directorate-General for Humanitarian Aid and Civil Protection (DG ECHO). This facilitated a coherent European disaster response during the numerous emergencies.

There is likely to be a substantial monetary benefit in cross-border continental-scale flood EWSs. In Europe, transnational flood early warning is undertaken by the Copernicus Emergency Management Service: Floods, which consists of the European Flood Awareness System (EFAS) and its global twin system, the Global Flood Awareness System (GloFAS).

Similar examples can be provided for GloFAS. In August 2016, flooding occurred along the Ganges River in India. According to India's Central Water Commission, the Ganges in the Patna district was just 8 cm below the highest recorded water level, which forced thousands to flee their homes into relief camps. GloFAS was able to provide flood forecast information several weeks in advance (Figure 3.25). However, it is also clear that significant training is still required in order for such forecasts to be useful and to enable decisions from probabilistic information (Pagano et al., 2014). Training needs to be provided within the relevant context of international, regional and local organisations. For example, GloFAS has provided training through the RIMES (Regional Integrated Multi-Hazard Early Warning System) and UN-ESCAP (United Nations — Economic and Social Commission for Asia and Pacific), with participants from national hydrometeorological services in Bangladesh, Bhutan, Nepal, India, China and Pakistan (via the internet) and representatives from several international organisations.

In a recent case study in Uganda, Coughlan de Perez et al. (2016) have shown that global systems combined with local expertise and knowledge have the potential to assist in reducing flood disaster impacts by triggering preventative action before flooding. The system for forecast-based financing automatically triggers action when a flood forecast arrives and before a potential disaster. While not a perfect indicator of flooding, GloFAS forecasts proved to be reliable in forecasting a specific chance of flooding (exceedance of a pre-defined danger level) and was useful as an EWS.

3.4.7 Communicating uncertainty and decision making

Decisions are taken at different stages in the production of a forecast, as well as after its public release (e.g. as a flood warning, often based on expert judgement). Human expertise is in constant interaction with automated tasks in flood forecasting (Pagano et al., 2016) and controls much of the output information of a flood forecasting system. Training and reforecasting of critical events increases the capacity to deal with uncertainty information and enables optimal decisions to be made (Ramos et al., 2013; Crochemore et al., 2016; Arnal et al., 2016). Risk-based decision-support frameworks have to be tailored to the problem in question but also flexible to allow different flooding situations and, often, unprecedented flood events, to be handled (Dale et al., 2014). Challenges at present include providing tailored warnings that are acted upon by responders and the public (Demeritt et al., 2013; Dittrich et al., 2016), and developing decision-support systems that can integrate the different stages of flood risk management, without losing information on uncertainty, warning time, forecast accuracy and reliability. This should help decision-makers to understand the strengths and weaknesses of a forecasting system for different scales and events.

Similarly, flood hazard and risk mapping also involves many layers of data collection and modelling output display. It is crucial that communication is ensured at all stages and that essential information for decision-making is not lost (see Chapter 4). Communication not only targets decision-makers at public or private companies, but also involves communication to the public and to experts (Environment Agency, 2015) who may prefer information to be described in terms of possible impacts. The visualisation of model outputs and maps is part of the communication process (Pappenberger et al., 2013). Usually, communication will cover information on alerts, watches and warnings, risk maps and vulnerable areas that can be potentially affected by floods of different magnitudes and return periods (100-year flood, 10-year flood, etc.), but also guidance on using and interpreting maps. It is important that communication follows Open Geospatial Consortium (OGC) standards, such as providing information as Web Mapping Services (WMS) or WaterML, so that it can be easily integrated into other systems and be more effective. The communication of flood hazard and risk and the associated uncertainties should be a strong focus at all stages in the prevention, preparedness, response and recovery cycle. It should also be active during recovery in order to facilitate post-event surveys, to speed up recovery with the help of local communities or to convey lessons learned (Marchi et al., 2009; Stephens and Cloke, 2014; Javelle et al., 2014).

Efficient communication is also dependent on how users perceive risk and understand uncertainty, and tend to act in the face of uncertain information (Ramos et al., 2010; Bubeck et al., 2012). A two-way approach can enhance, and even modify, established links between modelling outputs (hazard and risk maps) and social actions. Through an increased understanding of user needs and institutional and social vulnerability drivers (Rufat et al., 2015, Daupras et al., 2015), existing bottlenecks in flood response, such as areas of difficult access or with high rates of injuries and fatalities, can be detected and targeted in the maps. With time, behaviour changes can even bring modifications to the vulnerability zones and can modify flood risk maps that cross flood vulnerability with hazard. In this process, building trust and confidence is essential. Uncertainties are not necessarily unwelcome by the public and stakeholders (McCarthy et al., 2007), and explicitly acknowledging uncertainty in flood risk mapping is also valuable for decision-makers (Michaels, 2015). The communication of uncertainty can help modellers and forecasters by strengthening a relationship of confidence between them and the users of their products.

Flood forecasts and flood risk maps have associated uncertainties and are useful if decision-makers can understand and act upon the information provided, so forecasting and mapping must be in harmony with user needs and requirements to bring added value to the whole process of flood hazard and risk management.

One uncertainty that it is essential to consider in all aspects of flood risk management is the projected future changes in flooding risks to communities, businesses and infrastructure. This means considering adaptive management approaches in the design of flood risk management policy and infrastructure (Gersonius et al., 2013). The degree of uncertainty in the impacts of climate change projections requires the consideration of flexible adaptation pathways. Regardless of the sources of uncertainties, more needs to be done in flood risk management policy and practice to make our societies resilient to future flood risk (CCC, 2017; EEA, 2017).

3.4.8 Conclusions and key messages

Flood disasters affect a large number of people across the world every year, with severe social and economic impacts. Severe flooding repeatedly affects European populations, with trans-national events often being the most damaging.

Partnership

Our best strategy for flood management is to learn to live with flooding, that is, to prepare ourselves today to be better adapted for flood risks tomorrow. The combination of strong flood management policy, advanced early warning technology and increased international collaboration has the potential to reduce flood risk and improve disaster response from the local to the global scale. This requires stakeholders from different disciplines, scientists, policymakers and practitioners to work closely togetherin partnership.

Knowledge

Flood hazard and flood risk maps are required for land use planning, floodplain management, disaster response planning and financial risk planning. They can be produced at increasingly high resolution for fluvial and surface water flooding (and coastal flooding) using flood modelling tools. Uncertainties can be taken into account by using probabilistic methods. A focus on flood hazard impacts can enhance communication to the public.

Innovation

Flood forecasting and EWSs are innovations that are key preparedness actions for flood risk management and can be implemented at local scales through to continental and global scales. Radar and numerical weather forecasting systems can be used as inputs to flood forecasts, but uncertainties should be taken into account using ensemble (probabilistic) forecasting techniques.

There is probably a substantial monetary benefit in cross-border continental-scale flood EWSs. In Europe, transnational flood early warning is undertaken by the Copernicus Emergency Management Service: Floods, which consists of EFAS and its global twin system, GloFAS.

Flood forecasts and flood risk maps have associated uncertainties and are useful if decision-makers can understand and act upon the information provided, so forecasting and mapping must be undertaken in harmony with user needs and requirements to bring added value to the whole process of flood hazard and risk management.

3.5 Hydrological risk: landslides

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3.5.1 Introduction

The term landslide encompasses a wide variety of phenomena, from the simple fall of rock blocks from vertical rock faces, through to topples and landslides that are dominated either by a sliding motion or by flows of soil and/or rock. Landslides are strongly correlated with other types of natural hazards, such as floods, droughts, wildfires, earthquakes, tsunamis and volcanoes, and are often involved in cascading events of multihazard disasters.

Climate change, the increased susceptibility of surface soil to instability, anthropogenic activities, growing urbanisation, uncontrolled land use and the increased vulnerability of populations and infrastructure contribute to the growing landslide risk. In the Thematic Strategy for Soil Protection (European Commission, 2006), landslides are considered one of the main threats to European soils. In this framework, landslide disaster risk reduction should be properly undertaken in order to reduce the impact of landslides on humans, structures and infrastructures. In areas with high demographic density, protection works often cannot be built owing to economic or environmental constraints, and is it not always possible to evacuate people because of societal reasons. Forecasting the occurrence of landslides and the risk associated with them, and defining appropriate EWSs, are, therefore, essential needs.

The societal and economic impact of landslide risk is difficult to assess and it is underestimated, since a relevant part of related damage is attributed to other natural hazards, in multihazard chains (e.g. seismically induced failures, rainfall induced debris flows, lahars and rock avalanches associated with volcanism).

An established worldwide scientific landslide community has flourished in the last decades, thanks to several international organisations, such as the International Consortium on Landslides and the Landslide Joint Technical Committee, which periodically organise the World Landslide Forums and the International Landslide Symposia, respectively. Regular landslide sessions are also organised at the General Assembly of the European Geoscience Union each year.

The term 'landslide' describes a variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill or a combination of these.

In this subchapter, the main causes and triggers of landslides and their socioeconomic impact at European level are described, before some general concepts and methodologies on landslide zoning (inventory, susceptibility and hazard maps) and EWSs based on the analysis of landslide monitoring data and rainfall data are introduced.

3.5.2 Landslide causes and triggers

The most recent landslide classification is found in Hungr et al. (2014). It discerns five main types of movement: falls, topples, slides, spreads and flows. Many landslides consist of a variety of movement types occurring in sequence. For example, large landslides in high mountainous areas often start as rock falls involving freefalling rock that detaches from a cliff, which upon impact at the cliff toe may spontaneously transition into a very high-energy rock avalanche (Hutchinson, 1988). The properties of the flow change further as the landslide entrains or deposits debris and water.

Landslides vary greatly in size. At the largest scale, a single landslide can involve up to some cubic kilometres of rock and soils. At the other end of the scale, a small boulder has the potential to cause loss of life, if it strikes an individual, or to cause mass fatalities if, for example, it causes a train to derail. In general, the potential to cause loss scales with size of the landslide, largely because of the scaling of the kinetic energy and the affected area.

A key causal factor for landslides is the topographic setting of the potential site. In general, the propensity to failure usually increases as the slope angle increases, from essentially zero on a flat surface to a significantly higher level when slopes are steep. However, the relationship with geological factors is highly non-linear, and below a key gradient, any given slope is likely to be stable under most conditions. Slopes naturally evolve into a stable state under any given set of environmental conditions, primarily through landsliding processes. External factors disrupt the slope equilibrium to induce instability; thus, for example, a migrating river channel or an unusual flood may erode the toe of a slope, increasing the slope gradient and the likelihood of failure. The slope will then naturally evolve back to its stable gradient through time, perhaps by means of another landslide that removes the excess material.

A second set of causal factors relates to the type of material involved in the potential instability and its geotechnical properties, such as internal friction and cohesion. In hard rock masses, stability is usually defined not by the intact strength of the material but by the joints, fractures and faults. The strength of these discontinuities may be dramatically lower than the intact rock strength, especially where they are lined with a weaker material. Where such a discontinuity has an orientation that promotes failure, the resistance of the slope to landsliding can be dramatically reduced. Therefore, in many cases, analysis of susceptibility depends on an understanding of the role played by these discontinuities. Furthermore, the strength of slope materials degrades through the processes of weathering, which may physically and chemically alter the constituent minerals or may break an intact mass into smaller, weaker pieces. Therefore, the susceptibility of a slope to failure may increase with time.

Earth materials interact closely with hydrology and hydrogeology. Water is probably the most important factor that promotes slope instability. In many cases, water influences the strength parameters of geological materials, generally reducing strength when materials become saturated. Pore water pressure changes the effective stress state of a slope, typically reducing resistance to shear forces, and promoting instability. The lack of understanding of hydrological conditions is a frequent cause of failure in managed slopes; the 1966 Aberfan disaster in South Wales for example (Bishop et al., 1969), in which more than 140 people were killed by a landslide from a mine waste tip, was primarily the result of the construction of the tip on a spring and watercourse, which promoted conditions of full saturation after periods of heavy rainfall. However, water can also have more complex relationships with instability. For example, in some materials partially saturated conditions can provide additional strength through the generation of suction forces, while in others saturated conditions can promote soil liquefaction after failure, turning a slow landslide into a highly mobile and highly destructive flow.

Land use can also be a key factor in landslide causation. Some types of vegetation can improve stability by providing additional strength to the soil via root systems, and by regulating the infiltration of water and drawing down pore water pressures through transpiration. In general, forested slopes are more stable than those left bare, and there is a large body of evidence to support the argument that there is increased mudflow activity after fires have removed vegetation (Cannon and Gartner, 2005; Shakesby and Doerr, 2006) and increased landsliding after careless logging (Jakob, 2000). In general, the removal of vegetation promotes instability. Growing new vegetation is a difficult (but effective where successful) way to restore stability. Deforestation highlights the action of humans as the final key factor. As people modify the landscape, the likelihood of landsliding changes. In many cases, humans promote instability by cutting slopes to steeper angles, removing vegetation, changing hydrology and increasing weathering rates.

Landslide occurrence is related to causal factors, which create a propensity for a slope to fail, and triggers, namely the specific external event that induces landslide occurrence at a particular time.

In most cases, the timing of failure is associated with a trigger event. This is not always true, however; there is increasing evidence that slopes can fail through progressive mechanisms that involve the weakening of slope through time until stability is compromised, but such events are rare, although they can be destructive. However, most landslides are associated with a clearly defined trigger. Heavy rainfall is a key factor in generating landslides, primarily through the generation of pore water pressures and thus a reduction in the effective normal stress. For example, the annual global landslide cycle is dominated by the effects of rainfall associated with the South Asian and East Asian monsoons (Petley, 2010). The impact of the South Asian monsoon on the southern edge of the Himalayas, allied with the topography and materials of the region, makes this the global hotspot for landslide occurrence. However, the same correlation holds true everywhere.

The second key factor, and possibly the most important in terms of loss of life, is the impact of seismic events. Large earthquakes in mountain chains can trigger extraordinary numbers of landslides. Recent events include the 2005 Kashmir (Pakistan) earthquake and the 2008 Sichuan (China) earthquake, both of which killed more than 20 000 people in landslides. The Sichuan earthquake alone triggered more than 100 000 landslides. At present, the nature of the interaction between seismic waves and slopes is poorly understood, and forecasting the impacts of a future earthquake in terms of landslides is fraught with difficulty. However, the high levels of loss suggest that this will be a key area of research in the future.

Humans can also be a key trigger of landslides. The construction of hydroelectric stations can be significant. The Three Gorges Dam in China, the world's largest hydroelectric project, is expected to lead to the ultimate relocation of 1.4 million people owing to the construction of a 650-km long reservoir and the increased landslide risk; similar problems can be also found in Europe but to a lesser extent. The Vajont rock slide (Italy) resulted in the deaths of more than 2 000 people in 1963, when rock fell into the reservoir impounded by the highest arch dam in the world at the time. Humans trigger landslides through slope cutting (especially for road construction), deforestation, irrigation, undercutting and changes in hydrology and blasting, among many other activities. Mining activities have a particularly large impact. In more developed countries, mining is therefore strictly regulated; sadly, in less affluent countries, regulation lags considerably, and losses are much higher.

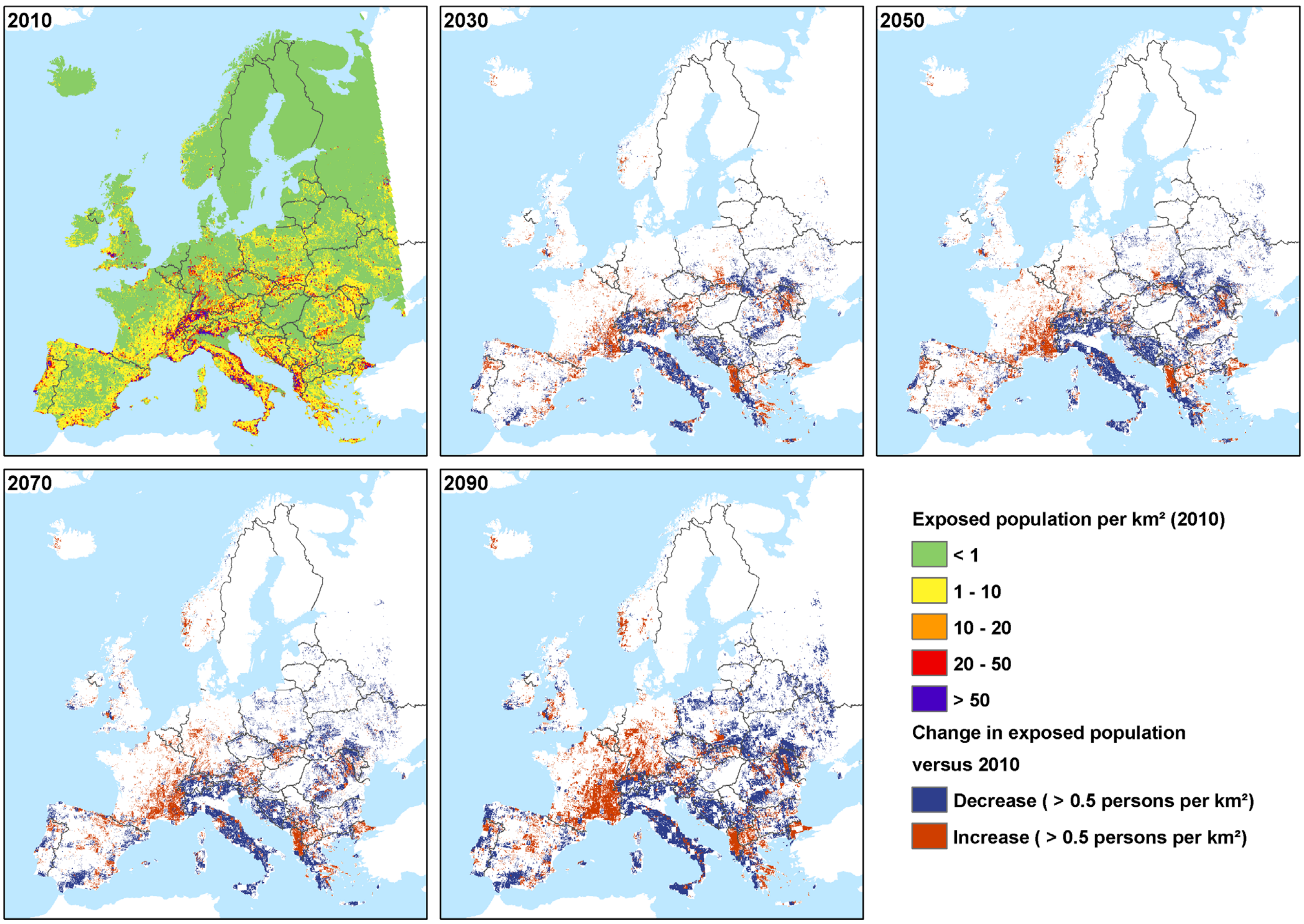
Finally, in active volcanic areas, landslides can be a major problem. Some of the highest levels of loss have occurred as a result of the high-mobility volcanic landslide known as a lahar, and volcanic flank collapses, which can be tsunamigenic, may be the largest terrestrial landslides possible. Some of the deadliest landslide events on record have occurred in volcanic areas. Active volcanism promotes instability (the 1980 Mount St Helens eruption started with a landslide that depressurised the volcano), and dome collapse is common. Volcanic deposits regularly mobilise into high-energy flows, and hydrothermal activity can cause material strength degradation over large areas. Major debris avalanches, partially submarine, were triggered by the 2002 eruption of Stromboli volcano (Italy) and they caused tsunamis, in a typical multihazard domino effect (Tinti et al., 2006).

3.5.3 The socio-economic impact of landslides in Europe and climate change

The fast-paced changes in society, climate change and the human impact on the environment have a major impact on the frequency and spatial distribution of landslides. Annual climate data in Europe for the last two centuries demonstrate a shifting pattern in frequency and intensity of extreme weather events (IPCC, 2012, 2013). Along with the changes in climate and weather patterns, demography, land use and other factors driving the landslide risk are changing rapidly (UN, 2015). Indeed, projections through the 21st century for Europe indicate that societal changes may lead to a larger increase in the impacts from landslides and other natural hazards than climate change. Therefore, the changes in the socioeconomic impact of landslides should be considered at two different timescales. The influence of climate change on the spatial and temporal characteristics of landslide risk will be noticeable by the end of the century. At a shorter timescale of one to two decades, the rapid changes in anthropogenic factors such as urbanisation and land use change drive the dynamic risk pattern that we face today.

FIGURE 3.26

Estimate of changes in the exposure of Europe's population to landslides in the 21st century
Source: SafeLand (2013)



Regional climate model (RCM) simulations from the EU FP6 project ENSEMBLES (Van der Linden and Mitchell, 2009) predicted a consistent large-scale pattern of heavy precipitation changes in Europe. The simulations generally showed an increase in heavy precipitation over northern and central Europe in winter, although some inconsistencies were found among the predictions from different models in mountainous regions and at the foothills of the mountains. In summer, most models agree on an increase in heavy precipitation over Scandinavia and reduced precipitation in southern Europe. The largest inconsistencies were found in the transition zone across central Europe, which separates areas with positive trends in the north and areas with negative trends in the south. Considering both the expected changes in patterns of extreme precipitation events and changes in other factors driving the landslide risk, the EU FP7 project SafeLand assessed the expected changes in climate-driven landslide activity (magnitude, frequency) in Europe in the next 100 years.

It must be emphasized that any prognosis of the changes in the socio-economic impact of landslides due to climatic change involves a high level of uncertainty.

The SafeLand study estimated that landslide hazard threatens about 4 % of European citizens today. In addition to the people directly threatened in their homes, 8 000-20 000 km of roads and railways are exposed to high landslide hazard, causing additional direct threats to life and economic assets as well as problems for emergency response and recovery operations (Jaedicke et al., 2013). The SafeLand prognosis was that about 0.7% of the total European population will experience an increase in landslide risk by the end of the century, although in some parts of Europe the risk will be reduced. The spatial pattern of the expected change in the European population exposed to landslide risk is depicted in Figure 3.26. The main changes in landslide risk at the European scale shown in the figure are due to the changes in population pattern caused by migration and urbanisation.

The SafeLand project also made a detailed study of the changes in landslide risk pattern at local scale for selected sites in Europe for the period 1951-2050. For these studies, the climate simulations were downscaled to simulate localised heavy precipitation events in regions where rain-induced landslides occur on a regular basis. The downscaled climate models predicted an increase in landslide hazard at all sites. These results differed from the predictions provided by larger scale climate models at some locations. These differences might be explained by the refinement in the climate model used, which, for example, considered the influence of local topography on precipitation. This demonstrated that large-scale models are useful to evaluate the relative spatial variations of landslide activity, while local scale models are necessary for urban planners and local authorities to estimate the future risks associated with landslides and other hydro-meteorological hazards in their communities or regions of interest.

In addition, the large uncertainties in population and traffic evolution scenarios, land use changes and political decisions regarding urban development require that the key parameters driving landslide risk are accurately monitored and that the prognosis of landslide risk is continuously updated as new information becomes available and more accurate and refined climate change models are developed.

3.5.4 Landslide zoning: inventory, susceptibility and hazard maps

The mapping of landslides underpins disaster risk reduction strategies, integrating socio-economic impacts, and therefore the challenge is to analyse their causes and triggers in our changing environments. Owing to the extraordinary breadth of the spectrum of landslide phenomena, no single method exists to identify and map landslides and to ascertain landslide susceptibility and hazard.

In addition to predicting 'where' a slope failure will occur, landslide hazard forecasts 'when' or 'how frequently' it will occur, and 'how large' it will be (Guzzetti et al., 2005).

The simplest form of landslide mapping is a landslide inventory map, which shows the location and, where known, the date of occurrence and the types of landslide that have left discernible traces in an area (Guzzetti et al., 2012). Landslide inventory maps can be prepared by different techniques, depending on their scope and the extent of the study area. Small-scale inventories (≤1:200 000) are compiled mostly from data obtained from the literature, through inquiries to public organisations and private consultants, by searching chronicles, journals, technical and scientific reports, or by interviewing landslide experts. Medium-scale landslide inventories (1:25 000 to 1:200 000) are most commonly prepared through the systematic interpretation of aerial photographs at scales ranging from 1:60 000 to 1:10 000, and by integrating local field checks with historical information. Large-scale inventories (>1:25 000) are prepared, usually for limited areas, using both the interpretation of aerial photographs at scales greater than 1:20 000, very high-resolution satellite images or digital terrain models, and extensive field investigations.

An archive inventory shows information on landslides obtained from the literature or from other archive sources. Geomorphological inventories can be further classified as historical, event, seasonal or multitemporal inventories. A geomorphological historical inventory shows the cumulative effects of many landslide events over a period of tens, hundreds or thousands of years. In a historical inventory, the age of the landslides is not distinguished, or is given in relative terms (i.e. recent, old or very old). An event inventory shows landslides caused by a single trigger, such as an earthquake, rainfall event or snowmelt event, and the date of the landslide corresponds to the date (or period) of the triggering event. Examining multiple sets of aerial or satellite images of different dates, multitemporal and seasonal inventories can be prepared. A seasonal inventory shows landsides triggered by single or multiple events during a single season, or a few seasons, whereas multitemporal inventories show landslides triggered by multiple events over longer periods (years to decades).

Landslide susceptibility is the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions. Landslide hazard is the probability that a landslide of a given magnitude will occur in a given period and in a given area.

Conventional methods to prepare landslide inventory maps rely primarily on the visual interpretation of stereoscopic aerial photography, aided by field surveys. New and emerging techniques, based on satellite, airborne and terrestrial remote sensing technologies, promise to facilitate the production of landslide maps, reducing the time and resources required for their compilation and systematic update. These can be grouped in three main categories, including the analysis of surface morphology, chiefly exploiting very-high-resolution digital elevation models captured for example by LiDAR (light detection and ranging) sensors, the automatic or semi-automatic interpretation and analysis of satellite images, including panchromatic, multispectral and synthetic aperture radar (SAR) images, and the use of new tools to facilitate field mapping.

Qualitative and quantitative methods for assigning landslide susceptibility can be classified into five groups (Guzzetti et al., 1999):

1. geomorphological mapping, based on the ability of an expert investigator to evaluate and map the actual and potential slope instability conditions;
2. analysis of landslide inventories, which attempts to predict the future landslide spatial occurrence from the known distribution of past and present landslides (typically, this is obtained by preparing landslide density maps);
3. heuristic or index-based approaches, in which investigators rank and weight the known instability factors based on their assumed or expected importance in causing landslides;
4. process-based methods that rely on simplified physically based landslide modelling schemes to analyse the stability/instability conditions using simple limit equilibrium models, such as the 'infinite slope stability' model, or more complex approaches;
5. statistically based modelling contingent on the analysis of the functional relationships between known or inferred instability factors and the past and present distribution of landslides. Regardless of the method used, it is important that the susceptibility zonations are validated using independent landslide information,

and that the level of uncertainty associated with the zonation is given (Rossi et al., 2010).

Landslide hazard is more difficult to obtain than landslide susceptibility, since it requires the assessment of the temporal frequency of landslides and the magnitude of the expected failures (Guzzetti et al., 2005). The temporal frequency (or the recurrence) of landslides, or of landslide-triggering events, can be established from archive inventories and from multitemporal landslide maps covering sufficiently long periods. Furthermore, where a landslide record is available, an appropriate modelling framework needs to be adopted (Witt et al., 2010). Alternatively, for meteorologically triggered landslides, one can infer the frequency of landslide events from the frequency of the triggering factors, for example the frequency (or the return period) of intense or prolonged rainfall periods. The uncertainty inherent in the prediction of triggers that may result in landslides adds to uncertainty inherent in the prediction of occurrence of landslides.

To determine the magnitude of an expected landslide, investigators most commonly revert to determining the statistics of landslide size (area or volume). Accurate information on landslide area can be obtained from high-quality geomorphological inventories. Determining the volume of a sufficiently large number of landslides is more problematic, and usually investigators rely on empirical relationships linking landslide volume to landslide areas (Guzzetti et al., 2009; Larsen et al., 2010; Catani et al., 2016). Finally, when determining landslide hazard as the joint probability of landslide size (a proxy for magnitude), the expected temporal occurrence of landslides (frequency) and the expected spatial occurrence (landslide susceptibility), great care must be taken to establish if, or to what extent, the three probabilities are independent. In many areas, given the available information and the local settings, this may be difficult to prove (Guzzetti et al., 2005). We expect that the quantitative assessment of landslide hazard will remain a major scientific challenge in the next decade.

Such identification of areas susceptbible to landslide hazard is essential for the landslide risk assessment and possible implementation of effective disaster risk reduction strategies. These strategies (Dai et al., 2002) include land-use planning, development control land, the application of building codes with different engineering solutions, acceptance, and monitoring and early warning systems. Land planning control reduces expected elements at risk. Engineering solution is the most direct and costly strategy for reducing either the probability of landsliding or the probability of spatial impact of a landslide. One approach is correction of the underlying unstable slope to control initiation of landslides (such as stabilisation of slope, drainage, retaining walls or planting), and the other is controlling of the landslide movement (such as barriers/walls to reduce or redirect the movement when a landslide does occur). The acceptance strategy defines acceptable risk criteria (Fell, 1994;Fell and Hartford, 1997); and the monitoring and warning system strategy reduces expected elements at risk by evacuation in advance of failure.

3.5.5 Landslide monitoring and early warning

These systems require a fine assessment of the socioeconomic impact of landslides, which must be based on accurate landslide mapping, as well as an understanding of their causes. EWSs for landslides are based on the reliable continual monitoring of relevant indicators (e.g. displacements, rainfall, groundwater level) that are assumed to be precursors to triggering landslides or reactivations. When values for these indicators exceed predefined thresholds, alarms are transmitted directly to a chain of people in charge of deciding the level of warning and/or emergency that must be transmitted to the relevant stakeholders, following a predefined process (Figure 3.27). In some cases, warnings can also be automatically transmitted. Usually, one to five alert levels are used (Blikra, 2008; Intrieri et al., 2013): the highest level may lead to emergency warnings to the population, evacuations or the use of sirens and loudspeaker messages in several languages to force people to move to a safer place, as in the case of tsunamis induced by landslides.

An EWS needs to be set up with specific requirements. First, the potential impacts must be defined based on a risk analysis informed by hazard mapping, including the impact of global changes (Corominas et al., 2014). In addition, the causes and triggers of disasters must be thoroughly analysed and the development of local coping capacities must be included (Dash and Gladwin, 2007).

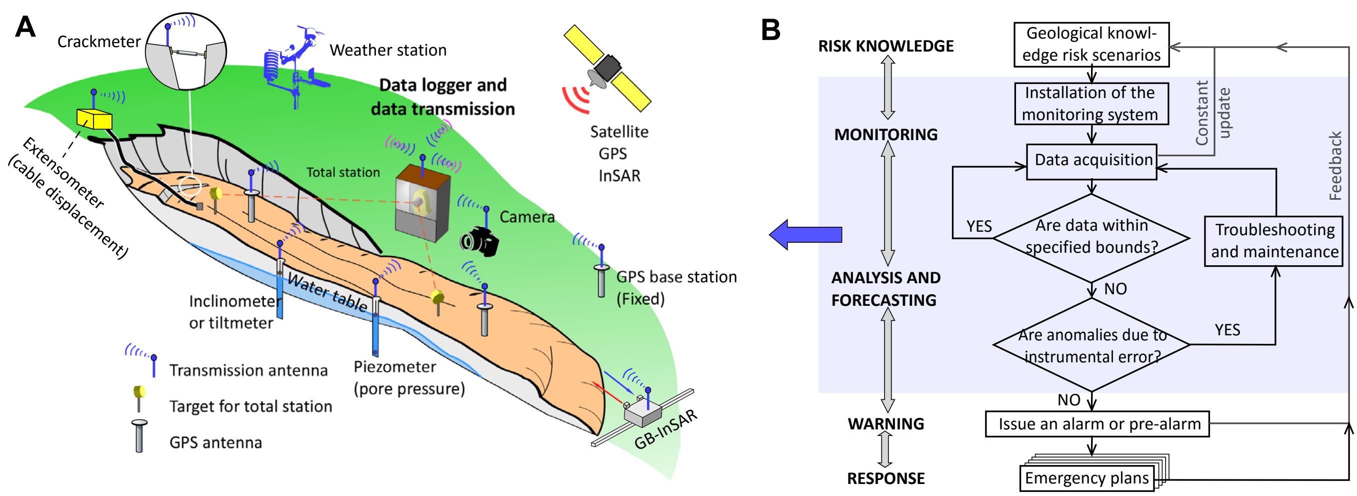
The number of EWSs dedicated to landslides has greatly increased since the beginning of the 21st century because of the progress made in electronics, communication and computer programs for monitoring and imaging. In addition, the innovations in satellite technologies and ground remote sensing have greatly improved the capacity of remote imaging measurements versus in situ point measurements (Tofani et al., 2013). Implementing an EWS depends on the context, namely (1) the type of landslide (Hungr et al., 2014), (2) the disaster scenarios considered, (3) the degree of awareness of the stakeholders, including populations, and (4) the allocated resources (e.g. budgetary, human).

Landslide types determine, first, if the appropriate EWS must be site specific or regional (Intrieri et al., 2013), and also if it is dedicated to identifying triggering conditions and/or to detecting an ongoing event (Sättele et al., 2016). For example, monitoring systems of debris-flow or shallow landslide EWSs are usually based on thresholds of rainfall amount over a period of time. These thresholds are based on rainfall intensity-duration, cumulated event rainfall-duration (Guzzetti et al., 2008), or antecedent precipitation (including snow depth) measures and soil moisture (Baum and Godt, 2010; Jakob et al., 2012). An extended monitoring of those indicators usually makes it possible, therefore, to set regional alarms. Landslide types also constrain the maximum lead time or time of reaction after the alarm transmission (Sättele et al., 2016). In some specific cases, debris-flow catchments are equipped with monitoring systems such as ultrasonic and seismic sensors that detect the debris-flow movements (Marchi et al., 2002) and automatically send a warning message to shorten the reaction time as much as possible.

For site-specific systems, displacements measured by different sensors and pore water pressure and/or precipitation are usually used (Michoud et al., 2013). Various sensors can be set to monitor displacements, including extensometers (cable or laser) and crackmeters that measure the distances between two points, and total stations that are also used to provide distances and 3D positions using targets positioned on site. Moreover, GPSs

FIGURE 3.27

(A) Illustration of the components of a modern EWS that does not show the energy sources and the two or three levels of redundancy. (B) Flow chart of the activities of the implementation and operation of an EWS (modified from Intrieri et al., 2012). The blue box in (b) indicates the action linked to the monitoring system. Source: courtesy of authors



are nowadays widely used, which can give the real 3D position of a point (Gili et al., 2000). All the above techniques usually provide data only at specific point locations; thus, several of them must often be set up in a network to monitor areal deformations. Inclinometers give deformations at depth along boreholes, providing essential data on the changes in depth of landslide behaviour (Blikra, 2008). For the last few years, ground-based interferometric radar (GB-InSAR) has been used for the most critical landslides (Casagli et al., 2010; Blikra, 2012; Rouyet et al., 2016). It provides a map of the distance changes, from the GB-InSAR to the landslide surface, at a millimetre scale and with a time resolution of a few minutes. Satellite InSAR images are also used to monitor long-term displacement trends, with results being strongly dependent on the type of treatment. In optimal cases, the time resolution is about 6 days, with millimetre precision and metre spatial resolution (Berger et al., 2012). Finally, as landslides react to water infiltration, many instruments are dedicated to monitor water: rain gauges, piezometers, thermometers, barometers, moisture content sensors and other meteorological data. Pore water pressure changes monitored with piezometers usually have a good correlation with slope movements (Michoud et al., 2013).

Behind the implementation of the monitoring part of EWSs is the understanding of the landslide mechanisms, that is, the identification of the main parameters controlling the movements of the landslide (Intrieri et al., 2012 and 2013). For this purpose, the design of a landslide conceptual model (LCM) is fundamental, since it will guide the type and the location of the sensors to install, and it is required to forecast landslide failure scenarios. The updating of an LCM must be continual during the whole life of an EWS. In addition, landslide failures may trigger other hazardous events in a cascade effect, such as tsunamis or dam breaks, that have to be considered in the EWS. The reasons why an EWS is implemented are either the identification of an unacceptable risk level or an increase in, or abnormal, landslide activity. Although the LMC implementation process provides reasons to fix appropriate sensors that will monitor the most significant failure initiation indicators, there are usually many practical constraints, such as topography, access, visibility and available resources.

Landslide monitoring and EWSs are tools to forecast the potential occurrence of disasters, thus contributing to the implementation of effective disaster risk-reduction strategies.

Ideally, the first data from a monitoring system are used to calibrate and fix alarm thresholds usually based on displacement velocities or accelerations, or pore water pressure or precipitations (Cloutier et al., 2015). This approach can be supported by failure forecast models, such as the Fukuzono method, or by more complex models (Crosta and Agliardi, 2003; Federico et al., 2012). The alarm thresholds will be used to trigger chains of actions that will involve different levels of people depending on the alert level, from technicians and experts to officers and politicians who will be involved in the assessment of the abnormal situations and who will have to make decisions (Froese and Moreno, 2014). This starts from the initial check of the situation and the coherence of the movement detection of the sensors (to avoid false alarm), and it can end with an evacuation decision. It requires that the monitoring system is reliable and is therefore redundant in terms of sensors, communication and the stakeholders involved. Pre-defined crisis units must follow decision trees to propagate or stop the warning at each level. This also necessitates the requirement to verify constantly that the observed landslide behaviour is still following the expected course, which also implies that the threshold and alarm levels can be reassessed by the crisis units.

The most important actions that can be prompted by EWS high-alert levels are evacuations and a rapid set-up of protection measures. They imply that all stakeholders, including the relevant population, must be prepared through education and training to implement the appropriate response.

In addition, the methods used to emit and communicate the emergency situation must be adapted to the local population culture. It must be stressed that all stages of implementation or operation must include feedback to the other stages. Frequent feedback and updates are a key point. They must also include the reappraisal of the indirect effects (cascade). A final problem relates to communication to the general population, which, to be effective, needs trust and training and must be an efficient means by which to communicate and emit warnings and actions within the noise of our 'connected world'. It appears that only 38 % of the EWSs have more than one communication vector to inform the population (Michoud et al., 2013).

3.5.6 Conclusions and key messages

Partnership

Understanding landslide risk requires a multihazard approach, based on networking and partnership between different scientific disciplines, with transdisciplinary research that aims to identify those socioeconomic and institutional elements that require attention in landslide DRM.

Knowledge

Knowledge of landslide risk is a multidisciplinary task that requires an understanding of processes and mechanisms, spatial and time prediction, vulnerability assessment, monitoring and modelling of the effects related to environmental and climate change.

Innovation

The effectiveness of landslide risk mitigation measures critically depends on scientific innovation and technological development for rapid mapping, monitoring and early warning.

3.6 Hydrological risk: wave action, storm surges and coastal flooding

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3.6.1 Overview of coastal flood risk

Coastal flooding is one of the most significant risks to life and infrastructure both globally and for Europe, with wide-ranging social, economic and environmental impacts. For example, in the United Kingdom alone, it is estimated that GPB 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding (Environment Agency, 2009). In Europe, long-term investment in operational flood warning systems has largely ensured that fatalities due to coastal flooding are avoided; however, the damage to infrastructure and clean-up costs are still significant. For example, during storm Xaver (4-8 December 2013) which brought the highest ever observed water levels to many European coastlines, there was no loss of life due to coastal flooding (although there were 15 fatalities directly associated with falling trees and vehicles). However, the financial impact of the severe coastal flooding was estimated by Credit Suisse to be more than EUR 1.5 billion.

In contrast to European weather systems, tropical cyclones can cause storm surges of up to 10 metres, which continue to cause devastating loss of life in parts of South-East Asia. In 1970, a devastating storm surge resulted in approximately a quarter of a million deaths in Bangladesh. Over the past decade, there has been considerable activity in the development of crucial flood warning systems for vulnerable tropical areas such as Bangladesh (DMB, 2010; WMO, 2010), resulting in the saving of tens of thousands of lives. However, despite the improving availability of coastal warning systems, tropical cyclones continue to cause havoc when this is a lack of preparedness. On 8 November 2013, Typhoon Haiyan (known as typhoon Yolanda in the Philippines) caused catastrophic damage throughout the Philippines, with the majority of the death toll (estimated to be more than 6 000 people) attributable to the storm surge that struck Tacloban City.

Coastal flooding is caused by a combination of high tides, storm surges and wave conditions. Development on floodplains increases the risk as do coastal erosion and sea-level rise.

Coastal flood risk is growing because of long-term mean sea-level rise and possible future changes in storminess (Church et al., 2013), as well as continued population growth and development in flood-exposed areas (Hallegatte et al., 2013). Irrespective of any future change in storm climate (which would affect storm surges and waves), mean sea-level rises will result in more instances of extreme sea-level thresholds being reached.

Coastal flooding occurs when a combination of high tide, storm surges and wave conditions is sufficiently severe to overtop or breach coastal defences and cause inundation of low-lying areas. Extreme high waters around Europe are normally caused by a combination of high tides and severe weather events (with the exception of the Mediterranean Sea where tides are small). Extra-tropical cyclones (the prevailing European weather systems) produce storm surges that can increase tidal levels by 3-4 metres in exceptional cases. The still water level (defined as the sea level before short-period waves are taken into account) can be further elevated at the coast by wave set-up caused by wave breaking. Storms then also produce large wind and swell waves, which can overtop coastal defences/beaches and cause flooding and erosion. A further factor that drives coastal flood risk is socioeconomic change (Thorne et al., 2007). Changes in land use and increasing asset values in floodplain areas have led to increased exposure to flooding (Horsburgh et al., 2010). Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne et al., 2007; Nicholls et al., 2015). As erosion is expected to dominate coastal morphological change in the future because of mean sea-level rises, this will add to the overall flood risk.

Waves and storms are a significant feature of global climate and have been included in many assessments of climate, including the latest assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). Recently, recognition of the central role of waves in atmosphere–ocean interactions has led to an initiative to include wave models more directly into climate model projections (Cavaleri et al., 2012; Hemer et al., 2012). The largest waves in European waters are found on the Atlantic boundaries, where waves can propagate over large fetches from the Atlantic Ocean. Many factors affect the height of waves in European waters, but for the Atlantic margin, the persistence and strength of westerly winds are particularly important (Wolf and Woolf, 2006), as are the intensity and frequency of storms. Waves are affected by currents and water depth and are locally modified by coastal geometry and man-made structures. Waves decrease in height in shallow water as a result of energy dissipation by bottom friction and wave breaking; this reduction in wave energy at a particular location may reduce over time, if the sea level rises, unless the coastal morphology in areas of mobile sediment can adapt at a similar rate (Woolf and Wolf, 2013). Extreme waves represent a hazard for any offshore operation or construction. Hazards may be due to, for example, large individual or significant wave heights, steep waves, crossing seas, or rapidly developing sea states (Toffoli et al., 2005). At the coast, wave overtopping or the impact of the waves on structures may become important. On longer timescales, changes in coastal wave climate may cause changes in the sedimentation and erosion patterns that in the long run will have impacts on sediment and shoreline dynamics (Wong et al., 2014). As sea levels rise and the rate of rise accelerates, low-lying coastal regions may be inundated, allowing waves to penetrate further inland, thus causing further damage.

3.6.2 Natural variability of waves, storm surges and mean sea level

All components of sea level display considerable natural variability, which influences the frequency of flooding on all timescales. Natural variability in the wave, storm surge and mean sea-level components ranges from variability associated with stochastic processes, to those displaying seasonal and longer period changes associated with regional climate (e.g. the quasi-decadal cycle known as the North Atlantic Oscillation - NAO). Europe experienced an unusual sequence of extreme storms over the winter of 2013-2014, resulting in some of the most significant coastal flooding since the catastrophic North Sea storm surge of 1953 (Matthews et al., 2014; Haigh et al., 2016).

Sea-level change at any particular location depends on many regional and local processes as well as global climate drivers, so regional sea-level change will differ from the global average. The fifth assessment report (AR5) of the IPCC concluded that it is very likely that the average rate of global averaged sea-level rise was 1.7 mm per year between 1901 and 2010 (IPCC, 2013). For the more recent period 1993-2010, this had risen to 3.2 mm per year, with consistency between tide-gauge and satellite altimeter data. It is likely that similarly high rates occurred between 1920 and 1950. Although there is a great deal of local variability in the measured values, mean sea levels around Europe (from tide gauge records) mostly exhibit

20th century rises that are consistent with the global mean value, although the central estimate around the United Kingdom is slightly lower than that of the global value (Woodworth et al., 2009). There is high confidence that the rate of observed sea-level rise increased from the 19th to the 20th century (Bindoff et al., 2007; Woodworth et al., 2011) and there is evidence of a slow long-term acceleration in the rate of sea-level rise throughout the 20th century (Church and White, 2011).

All components of sea level exhibit natural variability. There is no convincing evidence of observed changes in European storminess. Changes in extreme levels are driven by mean sea-level change.

Whether the faster rate of increase in sea level during the period from the mid-1990s reflects an increase in the longer-term trend or decadal variability is still not clear. For planning and engineering purposes, it is sea level with respect to the local land level that is of primary interest; furthermore, the Earth itself is moving as it recovers from ice loading during the most recent ice age. A key process that affects vertical land motion is the viscoelastic response of the solid Earth to deglaciation, termed glacial isostatic adjustment (GIA). An accurate understanding of regional sea-level change is a particular area that involves combining the global models of eustatic sea-level change (i.e. sea-level rise due to volume changes as well as geological changes to ocean basins) with local models of GIA modified localised effects at the coast (e.g. Smith et al., 2012). A further complication is that sea-level change is affected by large-scale gravitational adjustment in response to polar ice melt. Mitrovica et al. (2001) showed how rapid melting of major ice sources gives rise to spatial changes in the Earth's gravity field (as well as to the volume of water in the oceans); their model predicts a fall in relative sea level close to the source of melting as the gravitational interaction between ice and ocean is reduced, but a correspondingly larger rise in sea level further from the melt source.

Storm surges are the large-scale increases in sea level due to a storm. They can increase sea levels by 3-4 metres in European coastal seas and may last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors, including the intensity and track of the weather system, bathymetry and coastal topography. The same factors control storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water: most operational forecasting centres now systematically refer to the combination of a storm surge and tidal high water as a storm tide.

In a strongly tidal region such as the European shelf, it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied (e.g. Rossiter, 1961; Prandle and Wolf, 1978). The dominant mechanism for tide-surge interaction is increased water levels as a result of meteorological forcing that induce a phase shift in the tidal signal (Horsburgh and Wilson, 2007); many properties of a non-tidal residual time series (i.e. the time series of sea-level observations minus tidal predictions) are simply artefacts of small changes to the timing of predicted high water. The most useful measure of storm surges is the skew surge, which is the difference between the maximum observed sea level and the maximum predicted tidal level, regardless of their timing during the tidal cycle (de Vries et al., 1995). Hence, each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge. Williams et al. (2016) have now shown that the magnitude of high water exerts no influence on the size of the most extreme skew surges. This is the first systematic proof that any storm surge can occur on any tide, which is essential to understand worst-case scenarios. The lack of surge generation dependency on water depth emphasises the dominant natural variability of weather systems. Weak seasonal relationships between skew surges and tidal high waters have been identified, and the inclusion of these in statistical methods will improve the estimates of extreme sea levels.

Storm surges are, of course, generated by storms, and there has been much recent research aimed at understanding past and future changes in storminess over Europe due to the changes in mid-latitude storms over the North-East Atlantic. Trends in severe wind storms around the United Kingdom are difficult to identify, owing to the low numbers of such storms, their decadal variability and the unreliability of direct wind speed observations (Wang et al., 2009).

Wang et al.'s analysis shows that storminess conditions in this region have undergone profound decadal or longer timescale fluctuations, with considerable seasonal and regional differences. The most notable differences are seen between winter and summer, and between the North Sea area and other parts of the region. Over the last century the number of winter storms has decreased and then increased again. The observational evidence indicates that the strength of mid-latitude sea-level pressure (SLP) gradients and associated westerly circulation has increased in the northern hemisphere, especially during winter, since at least the late 1970s (Woolf and Wolf, 2013). The behaviour of North Atlantic storm tracks is key to understanding present and future changes in storminess. Future climate model projections have a large variability between models and a low signal-to-noise ratio for Europe compared with other mid-latitude regions (Hawkins and Sutton, 2009). Woollings (2010) identifies future European climate as particularly uncertain because (1) the spread between the predictions of current climate models is still considerable and (2) Europe is particularly strongly affected by several processes, which are known to be poorly represented in models, such as the small-scale structure of storms. Some of this variability seems to be related to the large-scale atmospheric patterns such as the NAO, which is related to the SLP difference between Iceland and the Azores. However, it is not clear that this relationship will persist into the future.

Wave climate in the North-East Atlantic and in European seas is to a large extent determined by the large-scale atmospheric circulation, the statistics of large-scale extra-tropical storms and smaller scale regional and local wind systems. Natural climate variability or anthropogenic changes in such factors will affect the wind climate, which results in corresponding changes to the wave climate. Changes in local wind climate will affect the wind sea, while changes in remote storm statistics will have an effect on the swell component of the wave climate. For the North-East Atlantic, Wolf and Woolf (2006) performed a number of sensitivity experiments with a numerical wind–wave model. By using synthetic wind fields, varying the strength of the prevailing westerly winds and the frequency and intensity of storms, as well as the location of storm tracks and the storm propagation speed, they found that variations in the strength of the westerly winds was most effective at changing mean and maximum significant wave height, while variations in other parameters had little effect on the mean wave height. Intensity, track and storm propagation speed, however, significantly affected maximum wave height. Generally, in all European Shelf seas and in the North-East Atlantic, pronounced seasonal variability in wave climate is seen with the highest waves in autumn and winter (e.g. Dodet et al., 2010; Arkhipkin et al., 2014).

Based on the assessment of literature analysing data from in situ measurements, satellite altimeter observations and wave model hindcasts, the IPCC AR5 concluded that it is likely that mean significant wave heights have increased in regions of the North Atlantic over the past half-century and that it is likely that these trends largely reflect natural variations in wind forcing (Church et al., 2013). For the North Sea and Baltic Sea, recent work is summarised in Huthnance et al. (2016) and Hünicke et al. (2015), indicating that wave height in these seas varies substantially on inter-annual and decadal timescales but does so far not show significant long-term trends. Using 20 years of buoy data for the Bay of Biscay, Dupuis et al. (2006) reported a tendency towards decreasing wave heights, which is consistent with the findings published in Dodet et al. (2010). For the Mediterranean Sea, Lionello and Sanna (2005) reported decreasing mean winter values of significant wave height in the period 1958–2001, while for the Black Sea, Arkhipkin et al. (2014) reported no significant change in corresponding storm activity.

The IPCC (2013) confirms that at most locations mean sea level is the dominant driver of observed changes in sea-level extremes, although large-scale modes of variability such as the NAO may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including Europe (e.g. Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea-level extremes, there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm surges (IPCC, 2012). The scientific consensus is that any changes in extreme sea levels at most locations are caused by the observed rise in mean sea level (e.g. Woodworth and Blackman, 2004; Menendez and Woodworth, 2010; Wahl and Chambers, 2016).

3.6.3 Datasets for coastal flood hazard analysis

The importance of having long time series data for assessing the statistics of extremes is well known (e.g. Weisse et al., 2009). A long time series of wave observations (at least 10 years and, ideally, 30 years) is required to describe the wave climate (Wolf et al., 2011). Such knowledge is required to characterise coastal vulnerability and to plan coastal management strategies. We know that there is also a large amount of inter-annual and inter-decadal variability, which can obscure any observation of long-term trends. There are few long-term wave datasets for European waters. One example is the United Kingdom Met Office Marine Automatic Weather Station (MAWS) system, which consists of various met-ocean recording systems, some of which have been maintained for several decades. A review by Hawkes et al. (2001) assessed the data available and led to the establishment of the CEFAS Wavenet network (n.d.). Data collected from the Seven Stones Light Vessel since 1962 led to the earliest observation of an increase in wave height in the North Atlantic (Bacon and Carter, 1991). This observation has since been validated and extended using altimeter wave data and models and attributed largely to changes observed in the North Atlantic atmospheric circulation patterns, principally the NAO (Woolf et al., 2002, 2003; Wolf and Woolf, 2006). Owing to the lack of long-term datasets, numerical models are often used to extend the time series, and many global and regional wave hind-casts and reanalyses are now available (e.g. ERA-Interim, ERA-20C from the European Centre for Medium-range Weather Forecasts (ECMWF, n.d.).

Datasets covering more than 30 years of wave observations are essential for flood hazard analysis. All coastal European countries store sea-level data. There are fewer wave datasets but satellite data are increasingly useful.

Long time series are increasingly available from satellite observations, although these are less reliable in the coastal zone. Improved algorithms now allow these data to be used closer to the coast (e.g. Gommenginger et al., 2010). Long time series data can also be generated using proxy data from time series of other variables (e.g. SLP data can be used as a proxy for storminess or can be generated from long hindcasts of dynamical models). Projections of future impacts that the relationships between proxy variables will remain the same in a future climate or may be made by running dynamic models into the future. Local impact models are highly dependent on the accuracy of projections of storminess in global climate models (where storminess may be defined as a measure of the frequency and intensity of storms).

Sea-level data from most European nations are archived and made available through their national data repositories. For instance, the British Oceanographic Data Centre is responsible for the remote monitoring and retrieval of sea-level data from the tide gauge network. These are then processed and quality controlled prior to being made available for scientific use. Several other European nations offer a similar facility (e.g. Système d'Observation du Niveau des Eaux Littorales, SONEL, in France and National Oceanographic Data Committee, NODC, of the Netherlands). For long-term sea-level analysis, a global record of sea levels is available from the Permanent Service for Mean Sea Level, which is responsible for the collection, publication, analysis and interpretation of sea-level data from the global network of tide gauges (PSMSL, 2017).

In order to better understand historical magnitudes and footprints of coastal flooding events for the United Kingdom, a systematic database of extreme sea level and coastal flooding has been compiled, covering the past 100 years (Haigh et al., 2015; www.surgewatch.org). Using records from tide gauges, all sea levels that reached or exceed the 1 in 5 year return level were identified. These were attributed to 96 distinct storms, the dates of which were used as a chronological base from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event, the database contains information about the storm that generated that event, the sea levels recorded during the event, and the occurrence and severity of coastal flooding that resulted. This database is continuously updated. Similar databases for Europe-wide flooding could be conceived and created.

3.6.4 Future climate projections of waves, storm surges and mean sea level

The IPCC (2013) has projected global sea-level rise for the period 2081-2100, compared with 1986-2005, to be 0.29-0.82 metres. The precise range varies with the assumed Representative Concentration Pathway (RCP) scenario, which describes the radiative imbalance in Earth's atmosphere due to greenhouse gas emissions. Unlike in the previous IPCC report, these projections now include a contribution from changes in ice-sheet outflow, for which the central projection is 0.11 metres (it should be noted that there is only medium confidence in the range of projected contributions from models of ice sheet dynamics). Nevertheless, these new projections are broadly similar to those in the earlier AR4 assessment (IPCC, 2007). It is very likely that the rate of global mean sea-level rise during the 21st century will exceed the rate observed during the period 1970-2010 for all RCP scenarios. Regional patterns of sea-level change in the 21st century still differ between models. However, about 70 % of the global coastlines are projected to experience a sea-level change within 20 % of the global mean sea-level change.

Some studies use simple statistical, so-called 'semi-empirical', models that relate 20th-century (e.g. Rahmstorf, 2007) or earlier (e.g. Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) temperature or radiative forcing (Jevrejeva et al., 2010) with sea-level rise, in order to extrapolate future global mean sea level. These models are motivated by evidence in the palaeo record of a connection between global mean sea level and temperature over glacial/interglacial timescales.

These models result in wider ranging, and typically larger, projections of sea-level rise than those obtained from physical process-based models. For example, Rahmstorf (2007) has projected sea-level rise by 2100 under a range of climate scenarios to be between 0.50 and 1.40 metres, and Vermeer and Rahmstorf (2009) suggested the higher range of 0.75 to 1.90 metres. Church et al. (2011) note that these models may overestimate future sea levels because of the exclusion of key non-linear processes and climate feedback mechanisms. In addition, future rates of sea-level rise may correlate less well with global mean temperature if ice sheet dynamics play an increased role in the future. Many national authorities have introduced high-end scenarios to aid contingency planning, the value of which justifies the numerous assumptions made. For the United Kingdom (Lowe et al., 2009), this low-probability but high-impact value was estimated to be 1.9 metres, which is consistent with physical constraints on glacier movement (Pfeffer et al., 2008); this value also encompasses the majority of semi-empirical model projections. For comparison, Katsman et al. (2011) used an alternative method to develop a high-end scenario of a 0.40- to 1.05-metre sea-level rise (excluding land subsidence) on the coast of the Netherlands by 2100. More recently, Jevrejeva et al. (2014) obtained a probability density function of the global sea level in 2100, suggesting that there is a 5 % or smaller probability of a global sea-level rise greater than 1.8 metres; this low probability upper limit combined expert opinion and process studies and also indicates that other lines of evidence are needed to justify any larger sea-level rise this century. It is very likely that global mean sea-level rise will continue beyond the 21st century. The thermal expansion of the ocean as a result of increased temperatures takes place over centuries to millennia; therefore, thermal expansion will continue beyond 2100, even if greenhouse gas concentrations are stabilised immediately (which is unlikely). Contributions to sea-level rise from ice sheets are expected to continue beyond 2100, but glacier contributions will decrease as the amount of glacial ice diminishes. Some models suggest sea-level rises of between 1 metre and 3 metres in response to carbon dioxide (CO_2) concentrations above 700 parts per million. Studies of the last interglacial period (e.g. Kopp et al., 2009) indicate a very high probability of a sea-level rise of 2 metres over 1 000 years, and cannot rule out values in excess of 4 metres.

Overall there is low confidence in

future storm surge and wave height projections because of the lack of consistency between models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). Numerous studies have used regional climate model forcing to drive storm surge and wave models to infer changes in extreme sea level for the Mediterranean (Conte and Lionello, 2013; Jordà et al., 2012; Marcos et al., 2011), North Sea (Debernard and Røed, 2008; Gaslikova et al., 2013; Howard et al., 2010; Woth et al., 2006), as well as the Atlantic coast of Europe (Lowe et al., 2001; Lowe et al., 2009; Lowe et al., 2010; Marcos et al., 2012) and Baltic Sea (Gräwe and Burchard, 2012; Meier, 2006; Meier et al., 2004), while the first pan-European study was by Vousdoukas et al. (2016a). Some of these studies suggested increasing levels of storm surge along parts of northern Europe.

While extreme sea levels could change in the future, both as a result of changes in atmospheric storminess and of mean sea-level rise, it is very likely that mean sea-level rise will continue to be the dominant control on upwards trends in extreme future coastal water levels. Vousdoukas et al. (2017; 2016a) concluded that that by the end of this century the 100-year extreme sea-level along Europe's coastlines is on average projected to increase by 57 cm for RCP4.5 and 81 cm for RCP8.5. The North Sea region is projected to face the highest increase in ESLs, amounting to nearly 1 m under RCP8.5 by 2100, followed by the Baltic Sea and Atlantic coasts of the UK and Ireland. Mean sea-level rise is shown to be the main driver of the projected rise in extreme sea-level, with increasing dominance towards the end of the century and for the high-concentration pathway. Changes in storm surges and waves enhance the effects of sea-level rise along the majority of northern European coasts, locally with contributions up to 40 %. In southern Europe, episodic extreme events tend to stay stable, except along the Portuguese coast and the Gulf of Cadiz where reductions in surge and wave extremes offset sea-level rise by 20-30 %.

Global mean sea level will rise between 0.3 metres and 0.8 metres this century. Larger rises are possible. There is low confidence in storm surge and wave projections due to climate model limitations.

Regarding possible future wave climate changes, the IPCC AR5 notes low confidence in projections of future storm activity and hence in projections of wind waves (Church et al., 2013). For the Baltic Sea, Groll et al. (2017) found changes in the wave climate towards higher significant wave height for most regions that were consistent across their ensemble simulations. They noted that these changes result not only from higher wind speeds but also from a shift towards more westerly winds. In a comparable study for the North Sea, Groll et al. (2014) found a robust signal in eastern areas, where wave height was projected to increase towards the end of the 21st century in most of the analysed projections. For the west European Shelf, Zacharioudaki et al. (2011) found an increase in mean and extreme winter significant wave height south-west of the United Kingdom and the west of France. Elsewhere, decreases were found. This is consistent with the results provided by Charles et al. (2012), Mentaschi (2017) and Perez et al. (2015) who projected a general decrease in wave heights in the Bay of Biscay and Atlantic Europe by the end of the 21st century. Zacharioudaki et al. (2011) further emphasised that swell and wind sea may show different developments. For the north-west Mediterranean Sea, Casas-Prat and Sierra (2013) found some increase in mean and extreme projected wave heights but noted that these changes were very much dependent on changes in wave direction and thus on wind direction in the global models that were not uniform. The findings are consistent with those for the Mediterranean Sea reported by Lionello et al. (2008, 2010), who projected a shift in the wave height distribution towards lower values. Similar changes are reported in Perez et al. (2015), who further noted that the decreases were larger for long-term and high-emissions scenarios.

The effect of sea-level rise on tides remains an open scientific question, since previous studies are not reaching consensus. There is observational evidence of changes in tidal constituents in the 20th century (Mawdsley et al., 2015) however the significance of the driving processes remains yet unresolved (Woodworth, 2010). Regional modelling efforts have shown that sea-level rises exceeding 2 m can affect tidal amplitudes and phases (Pickering et al., 2012). For smaller sea level rises (~1 m) some studies find significant tidal changes (Arns et al., 2015; Idier et al., 2017; Pelling and Green, 2014) whilst others report negligible effects (Lowe et al., 2001; Sterl et al., 2009; Vousdoukas et al., 2017).

3.6.5 Tools and methods for assessing coastal flood hazard

Downscaling from global to regional climate change projections is vital for the study of meaningful local impacts (Wolf et al., 2015). Downscaling is generally taken to refer to the generation of locally relevant data from the output of Global Circulation Models (GCMs). The aim is to use global-scale projections, using accepted greenhouse gas emissions scenarios, to generate regionally specific and useful forecasts, with increased spatial and temporal resolution, and including processes that are not resolved in the coarser resolution model. Downscaling can be done in several ways: (1) using process models, (2) using empirical/statistical relationships, and (3) using hybrid methods (e.g. pattern recognition). Nesting an RCM into an existing GCM is an example of the first method, termed dynamical downscaling. An RCM is a dynamic model that gives higher resolution results than a GCM. Downscaling can also be done using statistical regression. This aims to capture the essential relationships (often calibrated using relationships in the current climate) between the global model and local variables.

Extreme events are linked to coastal flooding and for that reason inundation maps are a crucial element for coastal management and engineering practices (Ferreira et al., 2006), and evaluation of adaptation options (Cooper and Pile, 2014; Hinkel et al., 2010). The most common and simple way to obtain inundation maps is the static inundation approach considering as flooded all the areas with elevation lower than the forcing water level, extensively used for studies of different scales (Hinkel et al., 2014; Hinkel et al., 2010; Vousdoukas et al., 2012b).

Statistical or dynamical downscaling methods can be used to derive local information from global climate models. Reducing uncertainties and connecting physical models to decision tools will assist coastal management.

However, given the high complexity of coastal flooding processes, several recent studies showed that that the static approach resulted in substantial overestimation of the flood extent compared to dedicated hydraulic models, especially in flatter terrains (Breilh et al., 2013; Gallien, 2016; Ramirez et al., 2016; Seenath et al., 2016; Vousdoukas et al., 2016b).

Intermediate approaches have been developed which are capable of reducing the computational cost by taking into consideration either only water mass conservation (Breilh et al., 2013), or aspects of flooding hydrodynamics (Dottori et al., 2016), or the presence of obstacles (Perini et al., 2016; Sekovski et al., 2015). More elaborate and more computationally intensive are dynamic models like LISFLOOD-FP (Bates et al., 2010), which despite being originally developed for simulating river flow processes, have been proven to be reliable also for coastal flooding applications, such as the reproduction of storm surge events (Ramirez et al., 2016; Smith et al., 2012) and the evaluation of future scenarios of sea level rise (Purvis et al., 2008). Finally, process-based models specialized for coastal hydro- and morpho-dynamics (Lesser et al., 2004; McCall et al., 2010; Roelvink et al., 2009; Vousdoukas et al., 2012a) would appear as the optimal option, however they come with the disadvantages of (i) increased computational costs, which are almost prohibitive for large scale application; and (ii) the fact that they require information about the nearshore topography in detail which is often not available.

Outputs from climate models of various resolutions are often used to force hydrodynamic impacts models such as wave and storm surge models (leading to models of coastal impacts such as flooding and erosion). Issues for these model couplings are (1) quantification of model accuracy for past events and (2) understanding the uncertainty for future projections. This uncertainty consists of (1) uncertainty in greenhouse gas emissions,

(2) uncertainty in climate model projections of sea level and storms and (3) uncertainty in the surge and wave models. As models improve, the model uncertainty may be reduced but there remains uncertainty in the emissions and some of the model physics. Increasingly, the outputs of physical models such as those described above are combined with socioeconomic data to provide a set of decision tools that allow coastal managers to assess and mitigate risk.

These so-called 'broad-scale assessment tools' (e.g. Gouldby et al., 2008) connect marine science to engineering and economics and are now widely used in national analyses of coastal flood hazard, helping to define the scale of the problem and the potential mitigations.

3.6.6 Conclusions and key messages

Partnership

There is a need for improved multidisciplinary connections between oceanographers, coastal engineers and coastal planners to deliver decision tools based on sound physical and economic models.

Knowledge

Flood severity analysis would benefit from a community-wide European database and analysis of historic storm events that resulted in coastal flooding, building on the model of Haigh et al. (2015).

Innovation

There are a number of priority knowledge gaps that need to be addressed to improve the ability of the scientific community to assess the hazard-related risk associated with sea-level extremes, storm surges and waves. First, we require an improved understanding of the processes controlling time mean regional sea-level rise, in order to provide accurate regional projections. This implies a more sophisticated combination of ocean and solid Earth models, as well as sustained and accurate monitoring of sea level so as to better analyse regional variability. Sea-level projections also demand improved modelling of physical processes that couple the ocean and the cryosphere in order to explore the plausibility of rates of sea-level rise outside that suggested by the current models.

Improved process understanding of regional sea-level change is essential, as are improvements to the representation of weather systems in climate models. Multidisciplinarity is needed to deliver economic planning tools.

To better understand the possibility of changes to future storminess and, therefore, storm surges and waves, requires improved high-resolution modelling of mid-latitude weather systems in climate models. This would lead to a more complete assessment of future changes in the wave and storm surge climate with reduced uncertainty.

Recommendations

A set of recommendations relating to the abovementioned hazards has been identified, based around the three pillars of the Disaster Risk Management Knowledge Centre (DRMKC):

Partnership

Recommendation 1: Improving preparedness for hydrological risks requires contributions from many different disciplines of knowledge. Efforts are needed to improve (1) risk governance, including institutional governance, legal provisions and financial instruments for planning, prevention and crises management; (2) our understanding of hazard modelling; (3) forecasts and predictions, from short to long lead time ranges; and (4) emergency response recovery, including coordination of local operations, assistance to affected communities and recovery of disrupted services. Communication with and engagement of the public and decision-makers is key to effectively integrate these layers and to improve preparedness.

Recommendation 2: Risk-based decision-support frameworks have to be tailored to the problem in question but also need to be flexible to allow different situations to be dealt with as well as often unprecedented hydrological events. Warnings need to be tailored to the specific circumstances so that responders and the public can act accordingly. Information sharing and increased communication with all stakeholders is therefore essential and needs to be fostered further.

Knowledge

Recommendation 3: Hydrological hazard and risk maps should be developed using probabilistic methods to reflect the uncertainty in the underlying data and models and to produce more robust estimates of risk. This is especially relevant considering the sensitivity of hydrological risks to a changing environment such as land use changes or climate change.

Recommendation 4: Forecasting and EWSs are identified as key preparedness actions for hydrological risk management and can be implemented at local scales as well as at continental and global scales. Continued efforts to improve these systems are necessary to increase preparedness and society's resilience to hydrological risks.

Recommendation 5: Hydrological forecasts and risk maps have associated uncertainties that require adaptive management approaches in the design of flood risk management policy and infrastructure. The large uncertainty in the impacts of climate change projections requires flexible adaptation pathways to be considered.

Recommendation 6: An improvement of the understanding of the processes controlling hydrological risk including a better representation of weather systems in climate models is necessary, in order to improve regional projections of hydrological risk under a changing climate.

Innovation

Recommendation 7: Operational flood EWSs currently have the capability to produce coarse-scale discharge forecasts in the medium-range and to disseminate forecasts and, in some cases, early warning products in real time across the globe, in support of national forecasting capabilities. With improvements in seasonal weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multimodel forecasts and grand ensemble techniques, responding to the requirement of developing multihazard EWSs for disaster risk reduction.

Recommendation 8: Improved decision-support systems need to be developed that can integrate the different stages of flood risk management, without losing information on uncertainty, warning time, forecast accuracy and reliability. This will help decision-makers to understand the strengths and weaknesses of a forecasting system for different scales and events.

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3.4 Hydrological risk: floods

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Chapter 3

Understanding disaster risk: hazard related risk issues

SECTION III

Meteorological, climatological and biological risk

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3 Understanding disaster risk: hazard related risk issues

Section III. Meteorological, climatological and biological risk

CONTENTS

Introduction

The following subchapters cover meteorological, climatological and biological risks. In terms of meteorological risks, hazards from different types of storm systems as well as extremes of temperature are covered. Climatological risks include droughts and wildfires, and the biological risks posed by epidemics and pandemics are also examined. Each of these hazards is described in turn:

- There are two types of storm in meteorology: (1) the hazardous weather phenomena themselves (e.g. windstorms, rainstorms, snowstorms, thunderstorms and ice storms) and (2) the meteorological features in the atmosphere or storm systems that are responsible for the adverse weather. The latter includes tropical cyclones, extra-tropical cyclones and convective systems.

- Temperature extremes are rare high- or low-temperature events that may occur over a range of time and geographical scales. They usually occur because of a change in the weather pattern over a few days or several weeks.

- In terms of climatological risks, droughts result either from a shortfall in precipitation over an extended period of time, from its inadequate timing in relation to the needs of the vegetation cover, or from a negative water balance due to increased potential evapotranspiration caused by high temperatures.

- Wildfires refer to fires affecting grasslands, shrublands and other non-forest land covers. Although they are mainly initiated by human actions, their intensity and the effects they cause are mainly driven by fuel condition and availability, vegetation structure and prevalent meteorological and topographic conditions, and thus they are termed a natural hazard.

- An epidemic is the widespread, and often rapidly extending, occurrence of an infectious disease in a community or population at a particular time. A pandemic is the extension of an epidemic to many populations worldwide or over a very wide area, crossing many international boundaries and affecting a large number of people.

All of these hazards can lead to a range of substantive direct and indirect impacts on human activity and infrastructure. Compared with other meteorological disasters, extreme temperatures (particularly high rather than low temperatures) can cause the most severe consequences in terms of human lives lost. Droughts can affect extended areas and large populations, putting socio-economic systems and the environment at risk. Wildfires emit large volumes of smoke and gases that can aggravate respiratory problems, resulting in the deaths of susceptible individuals. Demographic, physical, socioeconomic, behavioural and institutional factors may moderate a population's vulnerability to most hazards, particularly temperature extremes and epidemics. Thunderstorm asthma is a term used to describe an observed increase in acute bronchospasm cases following severe thunderstorms, which can have significant impacts on individuals' health and on health services.

Of particular concern is the evidence that human-related climate change is increasing the frequency of these hazards. The accelerated growth in global mean temperature since 1975 and the projected increase over the next several decades have implications for the occurrence of temperature extremes. A number of researchers have also highlighted the potential changes in fire climate regimes in different parts of the world, which may result in increased fire risk and an exacerbation of the effects of wildfires.

However, these hazards do not always occur in isolation and can often interact with or influence one another. This is explained in chapter 2.5 where evolution of risk can be even so complicated that one hazard changes the vulnerability conditions for the next. For example, epidemics of Rift Valley fever often commence when a period of drought is followed by flooding or intense rainfall, so climate perturbations may herald an increased risk of outbreaks in at-risk regions. Similarly, prolonged droughts and heat waves dry out fuels, creating conditions which can exacerbate uncontrollable wildfires.

The following subchapters describe the current knowledge regarding the risk assessment and management of each hazard in detail, identifying a set of recommendations for key stakeholders to reduce and manage their risks.

3.7 Meteorological risk: extra-tropical cyclones, tropical cyclones and convective storms

***Thomas Frame**, Giles Harrison, Tim Hewson, Nigel Roberts*

3.7.1 Storm types and associated hazardous phenomena

3.7.1.1 Storms

Conceptually, there are two types of storm in meteorology: (1) the hazardous weather phenomena themselves (such as windstorms, rainstorms, snowstorms, hailstorms, thunderstorms and ice storms (freezing rain)), and (2) the meteorological features in the atmosphere — the 'storm systems' — that can be said to be responsible for this adverse weather (notably tropical cyclones, extra-tropical cyclones and convective systems). These storm systems, which are a focal point in the following discussion, can be distinguished from one another by their mechanism of development (growth), their structure, their geographic location, their spatial scale and their typical lifetime. Other types of storm system do exist, but these can be considered subtypes of the three systems listed above.

3.7.1.2 Extra-tropical cyclones

Extra-tropical cyclones are large rotating weather systems that occur in the extra-tropics (more than 30° latitude away from the equator). They consist of an approximately circular region of low surface pressure, of a radius of 100-2 000 km, accompanied by cold and warm fronts. They typically develop in regions of strong horizontal temperature gradients, which are commonly denoted on a weather chart as a cold or quasi-stationary front. In turn, such fronts often connect to a pre-existing decaying extra-tropical cyclone, which itself is situated some way downstream (typically to the north-east). At the same time, high up in the atmosphere (around 10 km altitude) one commonly finds a jet stream relatively close by. Indeed, the intensity of an extra-tropical cyclone is closely related to the strength of this jet stream. The strongest extra-tropical cyclones occur in winter months when the jet stream is at its strongest.

Storm systems can be distinguished from each other by their mechanism of development (growth), structure, geographic location, spatial scale and typical lifetime.

Periods when the jet stream is unusually strong can lead to two or more strong cyclones occurring within days of each other. The total lifecycle of an extra-tropical cyclone from birth (genesis) through to development and on to decay (lysis) can occasionally be more than 10 days; however, somewhere in the range of 2-5 days is much more typical (Ulbrich, 2009).

The major hazards associated with extra-tropical cyclones are high winds and precipitation (rain and snow). Precipitation occurs primarily along fronts and, on average, is not particularly intense relative to that delivered by tropical cyclones and convective storms. However, when a cyclone is developing, some very heavy precipitation can occur, particularly in a narrow band just to the left (north) of the cyclone track. The band is ordinarily between about 20 and 200 km wide, depending on the scale of the cyclone. In addition, fronts connected to cyclones can sometimes become very slow-moving, remaining over the same location for many hours, and potentially up to 2 days, leading to large rainfall accumulations and potential flooding.

3.7.1.3 Tropical cyclones

A tropical cyclone is a rotating storm originating in tropical latitudes, with low surface pressure at its centre. These develop over warm oceans in tropical regions, have a radius in the range of about 100-500 km, and have a lifetime of between a few days and a couple of weeks. They also have a structure in wind, rainfall, temperature, etc., that is relatively axisymmetric (unlike extra-tropical cyclones, the structures of which are not generally axisymmetric). The development and maintenance of tropical cyclones requires that the ocean surface is very warm relative to the air above, and that the air above has high humidity (Emanuel, 2003). The requirement of a warm ocean surface beneath means that tropical cyclones will decay as they move inland. This makes them primarily a hazard for oceanic and coastal regions as well as for small islands.

For historical and cultural reasons, the strongest tropical cyclones are assigned different terminology in different regions of the globe. In the North Atlantic and North-East Pacific, they are called hurricanes; in the North-West Pacific they are called typhoons, and in the Indian Ocean and southern hemisphere they are simply called cyclones. The term hurricane is also sometimes used erroneously by the media to refer to extra-tropical cyclones that have hurricane-strength winds. Tropical cyclones lead to very intense surface winds (notably in a small annulus around the eye), as well as heavy rain and lightning. The most significant threat that they pose is coastal flooding from the associated storm surge.

3.7.1.4 Convective systems

Convective storms are produced by a localised rapid ascent of air, which is made buoyant by the heating of air near the Earth's surface or the cooling of air higher up, with the ascent of the air maintained by heat supplied by condensation of water vapour within it. The rapid ascent of air in convective storms often produces very heavy but relatively short-lived rainfall, thunder and lightning, as well as, potentially, hail, very strong wind gusts and even tornadoes. At their simplest, convective storms consist of a single short-lived convective cell, comprising one ascending and one descending column of air (updraft and downdraft).

Individual cells have diameters ranging from around a few hundred metres up to several kilometres. However, severe convective systems can comprise many cells organised into a larger coherent structure with diameters of up to a few hundred kilometres. These can persist for much longer than the individual cells, as new cells tend to replace old ones within the structure. For example, convective cells may be organised in a linear fashion into squall lines or derecho systems. They may also form part of a rotating system such as a supercell or a large meso-scale convective system. Convective storms mostly occur in the tropics and over land in summer or over the sea in winter in the extra-tropics.

3.7.2 Frequency and geographical distribution of severe storm related hazards

3.7.2.1 High winds associated with extra-tropical cyclones

Extra-tropical cyclones account for the majority of recorded high surface winds in Europe. Their capacity to travel inland, and the fact that some cyclones are themselves very large, means that the winds associated with a single storm system can affect large areas. For example, as extra-tropical cyclone Kyrill (January 2007) travelled across Europe wind gusts of 25 m/s or more were reported over most of Ireland, the southern United Kingdom, northern France, the Netherlands, Belgium, Germany, Switzerland, Austria, the Czech Republic, Slovenia, Slovakia and Poland (Fink et al., 2009; RAIN, 2016). Cyclone Kyrill caused 46 fatalities (EEA, 2011), created total estimated insured losses of between EUR 4.5 and EUR 4.8 billion (EEA, 2011; AIR Worldwide, 2015) and a total estimated damage of EUR 7.7 billion. An example of a much smaller but much more intense storm system for which the economic losses were about the same was Cyclone Lothar, in December 2009 (Mitchell-Wallace and Mitchell, 2007; Roberts et al., 2014). Lothar affected only a relatively narrow swathe of northern France, south-west Germany and Switzerland, but wind gusts widely exceeded 35 m/s. An important consideration regarding impacts is that damage is typically estimated to vary according to gust strength to the power of 3 (Leckebusch, 2007). Therefore, 35 m/s gusts are much more destructive than 25 m/s gusts.

Understanding of the structure of extra-tropical cyclones has increased considerably in recent decades (see, for example, Browning, 2004; Hewson and Neu, 2015), to the extent that we now have a much clearer picture of related windstorm subtypes. Figure 3.28, for example, shows windstorm footprints for the subtypes Warm Jet (WJ), Cold Jet (CJ) and Sting Jet (SJ). These subtypes are important because they can explain differences in damage levels and the geographical extent of damage between different cyclones. For example, for Cyclone Kyrill, the subtypes were WJ and CJ, while for Cyclone Lothar they were probably WJ and SJ. Moreover, these different subtypes have very different associated predictability levels. WJ is relatively easy to predict, while SJ, the most extreme type, is notoriously difficult.

Storm systems lead to a variety of hazardous phenomena, including high winds, precipitation and lightning, with the spatial extent and duration of the hazard being strongly dependent on the type of storm.

Extra-tropical cyclones are ubiquitous in the extra-tropics, occurring at all locations and all year round (although they are more frequent and, on average, more intense in late autumn/winter). Europe is affected by about 10 extra-tropical cyclones per month (based on Hoskins and Hodges, 2002); however, the vast majority of such cyclones do not lead to damaging winds. These cyclones originate from three main sources. The main subtype affecting Europe is Atlantic cyclones, which typically form near the eastern seaboard of the American continent and develop as they cross the Atlantic over the course of several days, although such cyclones can also form over the eastern North Atlantic, closer to Europe. They may also develop over the Mediterranean (Mediterranean cyclones) or in polar regions (polar lows). Within the Mediterranean and in polar regions, cyclones can sometimes have some of the physical characteristics of tropical cyclones (leading to the term 'medicanes' in the former case), although such storms are not as long lived and the most extreme cases are much less severe than the most extreme tropical cyclones (Cavicchia et al., 2014). The frequency with which severe cyclones occur is difficult to define because the observational record is not sufficiently long (Della-Marta et al., 2009; Welker et al., 2016) and because current climate models, which could in principle, generate very long synthetic representations of the current climate on which to base an accurate estimate, typically lack the resolution needed to represent severe windstorms (Zappa et al., 2013; Donat, 2011). In addition, if severe cyclones cluster as has been suggested by Pinto et al. (2013) and others, then frequency estimates such as return periods need to be interpreted carefully.

The effect of climate change on the intensity and distribution of extra-tropical cyclones is still very uncertain; however, the IPCC AR5 (IPCC, 2014) states that it is unlikely that the number of cyclones will reduce by more than a few per cent and that there could be a small northward shift in the average tracks of extra-tropical cyclones relative to now. It is also noted that there is little evidence in one set of climate change simulations (CMIP5) of a change in extra-tropical cyclone-related wind strengths.

3.7.2.2 High winds associated with tropical cyclones

With the exception of Hurricane Vince in 2005 (Franklin, 2006), tropical cyclones are not known to reach Europe, although they may enter the region of the jet stream and evolve in structure into extra-tropical cyclones in a process known as extra-tropical transition. Some recent studies have suggested that there may be an increase in these transitioning cases during autumn due to a poleward expansion of the region of tropical cyclone development (Haarsma et al., 2013).

In subtropical coastal regions, tropical cyclones are a major cause of wind damage, particularly in the developing world, where infrastructure is not resilient to the magnitudes of winds that occur. The effect of climate change is likely to be a reduction or no change in the frequency of tropical cyclones, although the average strength of the associated winds is expected to increase (IPCC, 2014).

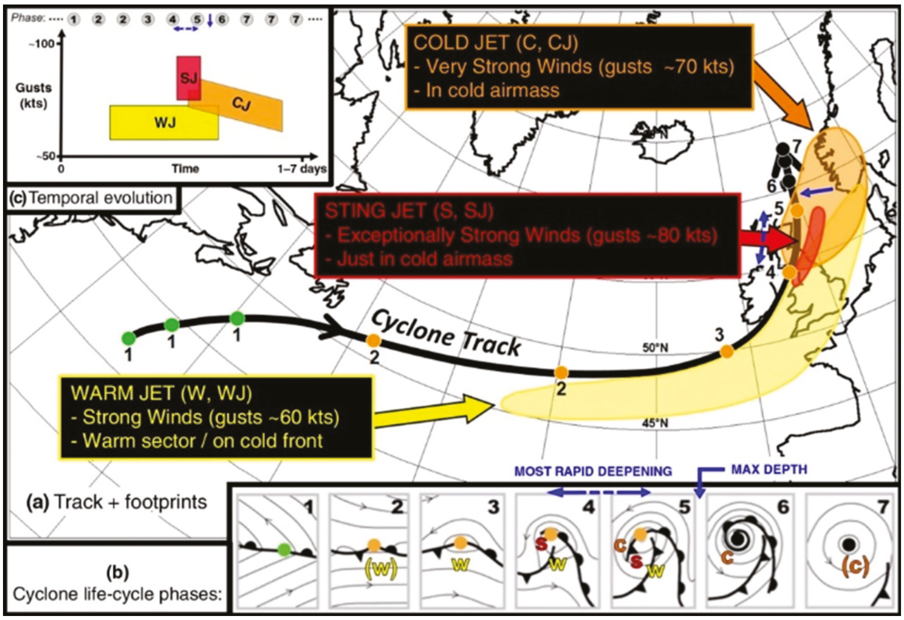
3.7.2.3 High winds associated with convective systems

Winds associated with convective systems can be extreme, the causes being both downbursts and tornadoes (weak tornadoes also occur, rarely, in frontal regions in extratropical cyclones). A key difference compared with cyclone-related winds is that convective system winds are relatively short-lived, and so impacts are very localised. Indeed, if plotted on a map similar to that in Figure 3.28, footprints associated with convective systems would be minuscule. Because of their small scale and relatively short lifetime, such events are difficult to observe and, therefore, full knowledge of their frequency and spatial distribution is difficult. Moreover, it is very likely that there is under-reporting, particularly in sparsely populated areas.

In recent decades, approximately 240 tornado sightings have been reported in Europe each year (Antonescu et al., 2016). These were mostly in summer, in mid to late afternoon, when convective activity is highest. The small scale and short lifetime also mean that when they do occur they present a hazard for only a very small area; however, the degree of hazard can be exceptionally high, because of the extreme wind strengths that are possible. The direct measurement of tornado winds is not feasible owing to their destructive nature, although progress has been made with the introduction of mobile Doppler radar, which can make indirect measurements remotely. Occasionally, large convective storm systems can form into squall lines (or derechoes), which can cause a swathe of damaging winds over larger areas. One example is the derecho that hit Berlin in 2002 and caused considerable damage and four fatalities (Gatzen, 2004); another is the events of 9 June 2014 in western Germany that killed six (BBC News, 2014). In both such cases, footprints were still no more than about 25 % of the size of the red SJ zone in Figure 3.28.

FIGURE 3.28

Conceptual model of the footprints of windstorms associated with extra-tropical cyclones.
Source: Hewson and Neu (2015)



3.7.2.4 Precipitation: rain, snow and hail

All storm types are associated with some form of precipitation. The exact nature of this depends strongly on the storm itself. The most frequent type of precipitation is rainfall. This presents a particular hazard when accumulations (the total amount of rainfall in a given time) over a local area or river catchment are large. This occurs usually from either severe convective rainfall, especially when the convection persists or is triggered repeatedly over the same location, or just to the left of the track of a rapidly developing extra-tropical cyclone, or on slow-moving fronts associated with such cyclones, or in and just downwind of upslope areas during periods of persistent, strong, moist, low-level flow (orographically enhanced rain). In the last two cases, the rainfall rates themselves may not be very large but the stationarity of the pattern is a key factor. Sometimes even fast-moving supercell storms or organised squall lines can produce flooding simply because of the sheer intensity of the rain.

Heavy snowfall has similar causes to heavy rainfall, as discussed above, but there are two key differences. The first is that, in all instances, the low-level air clearly needs to be sufficiently cold, and this tends to depend primarily on time of year, but also on proximity to coasts and other factors. The second is that extreme convective snow occurs only in certain small areas of certain countries, whereas convective rainfall extremes are much more evenly distributed across the world. Vulnerable areas lie adjacent to bodies of water such as lakes or oceans, which provide both the moisture source for the snow and perpetual triggering of convection, via the elevated surface temperature of the water body. Over the vast majority of the United States, a convective snowfall of 50 cm in 1 day is virtually impossible, but around the Great Lakes, it is not that unusual. Water bodies around Europe (e.g. the Baltic Sea, North Sea and Adriatic Sea) can also trigger extreme localised convective snowfall.

Hail is formed only in strong convective updrafts; the stronger the updraft, the larger the hail can be. Since hailstorms are small scale, it is difficult to get a precise picture of the geographical distribution and frequency of occurrence of hail by size (Hand and Cappelluti, 2011). Pocakal et al. (2009) suggest that the largest hail typically occurs in mountainous regions where updraft strengths can be large owing to the air being forced to rise over terrain. Reports of large hail (diameter of 20 mm or more) within Europe vary between zero and three reports per year per 10 000 km^2 depending on location; however, inhomogeneities in the observation network mean that confidence in published geographical distributions cannot be very high (see Hand and Cappelluti, 2011).

3.7.2.5 Lightning

Lightning strikes usually occur in the presence of convective rainfall associated with convective storms and tropical cyclones, although they may also occur in the frontal regions associated with extra-tropical cyclones. The number of lightning flashes per year is estimated to be of the order of 1-2 billion globally (Mackerras et al., 1998; Christian et al., 2003), with approximately one-fifth of flashes caused by lightning striking the ground and four-fifths caused by lightning between clouds (Mackerras et al., 1998). Over Europe, lightning strikes to the ground are estimated to vary between 0.1 and 4 times per year per square kilometre depending on location (Anderson and Klugmann, 2014). The response of lightning to a changing climate is poorly known, but it is expected to be highly sensitive to increasing global temperatures (Price, 2009).

3.7.2.6 Estimating potential for future severe storm related events

There are a number of ways to estimate 'potential worst case scenarios' in the current climate, although these will inevitably have error bars associated with them. For future climate predictions, the problem is much more challenging. For the current climate, one method is to assume that small-scale extreme events, seen in the instrumental record, could by chance have occurred in a nearby location. However, one must have due regard to physical mechanisms, so extreme orographic rainfall, for example, could not have occurred over flat plains situated close to mountains.

A second method is to use a state-of-the-art numerical model to synthesise possible realisations of the current climate. This is relatively common practice within the reinsurance industry, where extreme windstorms are simulated and their output is fed into impact models to estimate potential losses. The companies then position themselves financially to be able to cover such losses should such a storm occur. More recently, the ECMWF has pioneered a method of using operational reforecasts to estimate potential extreme rainfall events in the United Kingdom (Lavers et al., 2016). The main conclusions of this study were: '*Across half of the country at least 30 % more rainfall is possible. In some places, the potential maximum is substantially higher, up to twice what has occurred*'. Such an approach could be extended and expanded, to provide input for strengthening resilience networks.

A third method is to use a stochastic/statistical approach. This approach involves randomly generating a large number of artificial weather events (e.g. windstorm footprints) by, for example, decomposing observed storm structures into base elements using image processing techniques, and recombining these elements with random weighting factors to produce new storm structures. This is also employed in the reinsurance industry.

3.7.3 Forecasting and monitoring

3.7.3.1 Current predictive capabilities and future developments

Weather forecasts are produced using large computer models of the atmosphere that propagate the current best estimate of the state of the atmosphere forward in time. The atmosphere is a chaotic system, which means that there are inherent physical limits to how far into the future accurate forecasts can be made. However, over the past few decades, major improvements in forecast accuracy have been achieved through a combination of improved computer power, improved models and improved use and quality of observations (Bauer et al., 2015). Determining the extent to which forecasts can be further improved is a challenging scientific problem, which depends in part on the resolution of computer hardware issues, although there is no clear evidence as yet of any plateauing out of forecast accuracy. No forecast can ever be 100 % accurate, but larger scale atmospheric phenomena can be more accurately forecast further into the future than smaller scale physical phenomena (as illustrated by Table 3.2). To quantify the uncertainty, weather forecasts at all lead times are now typically produced using multiple computer forecasts (an 'ensemble forecast system') that each use slightly different (but plausible) initial conditions; the degree to which these forecasts differ gives an estimate of the degree of uncertainty in the forecast.

After their initial development, tropical and extra-tropical cyclones are coherent structures that can be tracked in time until they decay. The forecasting problem for such storms can generally be thought of as comprising several components: forecasting the genesis of a storm, forecasting its path and evolution of its structure and forecasting the severity of the associated weather.

Forecasting the genesis of storm systems is one of the most difficult tasks, as storm systems develop from small perturbations in regions of instability. A particularly challenging problem arises when convective cells combine into more organised structures: this includes tropical cyclones (see Majumdar and Torn, 2014), mesoscale convective systems and derecho storms. The formation of tropical cyclones is not completely understood, although several theories exist and some are being actively tested in field campaigns (Montgomery et al., 2012).

Despite a degree of uncertainty in forecasting, it has become more accurate over the past few decades, allowing mitigating actions to be taken and emergency services to be prepared in advance.

Because of their longer lifetimes, the existence of potentially hazardous extra-tropical and tropical cyclones can now be predicted with some confidence up to about 5 days in advance. However, at such leads, uncertainty in the details of a storm's track, timing and intensity are likely to be very large (Magnussen et al., 2014; Frame et al., 2015). For example, it may often be possible to state with confidence that a strong extra-tropical cyclone will occur, but uncertainty will remain with regard to the path it will take and the strength of winds and precipitation (see third column in Table 3.2). Nonetheless, for some users, having early indications of a very high potential for an extreme event, even if the point probability is only 5 %, can still be useful. Some basic mitigating actions can be taken, and emergency services can be placed in a state of readiness (Petroliagis and Pinson, 2014).

Owing to their small spatial scale and short timescale, unorganised convective storms cannot be forecast far into the future (see Table 3.2). The forecast chance of a thunderstorm occurring at a particular location remains negligible, even at lead times of a few hours. However, the background conditions that may give rise to the development of individual storms does have predictive skill (i.e. prediction of the instability in the atmosphere). It is, therefore, sometimes possible to provide a useful probabilistic estimate that convective storms will occur somewhere within a region within a time window. This has motivated a move to short-range local-area ensembles running at 'convection-permitting resolutions', requiring horizontal grid spacing of 1-3 km.

For example, the Met Office MOGREPS-UK 12-member ensemble forecast with 2.2-km grid covering the United Kingdom became operational in July 2012; the COSMO-DE 2.8-km ensemble (Gebhardt et al., 2011) became operational in a domain over Germany in May 2012, and the 2.5-km AROME model has been tested in several domains across Europe (Vie et al., 2011; Bouttier et al., 2012; Nuissier et al., 2016).

3.7.3.2 Use of observational updates/nowcasting

Although predicting a rapid intensification phase for cyclones can be very problematic, there are nonetheless operational tools available to assist with this. Commonly, forecasters compare imagery signatures, surface pressure measurements and other observations with their equivalent representation in a forecast model output to see if the forecast model is 'on track', and if it is not adjustments are made based either on selecting out a suitable ensemble member or on physical understanding and experience. It is of particular importance that forecasts are interpreted with the help of qualified meteorologists and forecasters (Heizenreder et al., 2015).

For convective storms, the high level of uncertainty in the location of storm formation and the short lifetime of storms means that while forecasts can provide initial indications that a severe convective storm is a possibility, much more detailed information is likely to emerge in near real time as the storm develops. For example, in the United States the average lead time for tornado warnings issued by the National Centre for Environmental Prediction (NCEP) increased from 3 minutes in 1978 to around 14 minutes in 2007 (Wurman et al., 2012), but warnings are still based primarily on the detection of tornadoes in observational data after tornadogenesis has occurred, and the improvement has been due to better observations and communications (Brotzge and Donner, 2013). Within Europe, recent improvements in radar networks in particular mean that there is greater potential for tracking severe convective events in real time than previously existed. For example, the installation of Doppler and dual polarisation radar give information about winds and more detailed information about droplet size and type within convective storms. Methods are used that project the track of a storm over the next few hours with the assumption that the storm will remain intact and that no new storms will form. These 'advection nowcasting' systems can be very useful for the first hour or so, but the rapid evolution of storms can quickly damage performance. In the future, it is expected that convection-permitting numerical models will be run much more frequently (hourly or more often) and combined with advection nowcasting to give the best probabilistic forecast.

3.7.3.3 Severe weather warnings

The technical challenge of disseminating information to the general public can increasingly be met through the worldwide web (e.g. meteoalarm.eu and National Meteorological services websites) and the adoption of smartphone applications (e.g. Deutcher Wetterdeinst's Wetterwarn APP, or weather apps produced by MeteoSwiss, the Met Office and Finnish Meteorological Institute). However, by providing the potential for mass communication to far more individuals and groups than ever before, this technology also creates a greater challenge in maintaining the National Met Service as a 'single authoritative voice' in issuing warnings (WMO, 2017) than was previously the case when mass communication was dominated by a small number of media organisations.

Severe weather warnings and guidance pose several other decision-making and communication challenges. Determining what degree of certainty in the forecast is required to for a warning to be issued is a non-trivial problem, which requires balancing the risk of missing the opportunity for early warning with the risk of issuing too many false alarms (Petroliagis and Pinson, 2014). Kox et al. (2015)

TABLE 3.2

Estimated current predictive capabilities in Europe for different hazardous weather phenomena discussed in the text. For this table the maximum lead-time for deterministic predictions (*) is taken to be the point beyond which deterministic forecasts, of threshold exceedance at a point, are more likely to be incorrect than correct (i.e. the 'Deterministic limit', following Hewson, 2006).
The maximum lead-time for useful probabilistic predictions (**) is taken here to be the lead time at which one can reliably highlight when the probability of a 1 in 20 year event (for a given day), at a point, exceeds 5 %. For thunderstorms (^), it is difficult to define the meaning of a 1 in 20 year event. Note that lead times quoted are approximate 'best guess values' for current forecasting systems based on forecaster experience and are for illustrative purposes.

Storm system	Storm type (weather)	Maximum lead time for accurate "deterministic" predictions *	Maximum lead time for useful 'probabilistic' predictions of an exceptional event**
Extra-tropical cyclones (Figure 3.28)	Rainstorm ('left of track')	≈24 hours	≈72 hours
	Rainstorm ('slow-moving front')	≈24 hours	≈96 hours
	Rainstorm ('orographic rain')	≈48 hours	≈144 hours
	Windstorm — CJ	≈24 hours	≈96 hours
	Extreme windstorm — SJ	≈2 hours	≈36 hours
	Snowstorm ('left of track')	≈12 hours	≈48 hours
	Ice storm	≈12 hours	≈72 hours
Tropical cyclones	Rainstorm	≈72 hours	≈120 hours
	Windstorm (broadscale)	≈48 hours	≈144 hours
	Extreme windstorm (near eye)	≈12 hours	≈72 hours
	Storm surge	≈24 hours	≈72 hours
Convective systems	Rainstorm ('flash floods')	≈30 minutes	≈48 hours
	Hailstorm	≈15 minutes	Not currently possible
	Windstorm (convective gusts)	≈15 minutes	Not currently possible
	Tornado	Not currently possible	Not currently possible
	Thunderstorm	15 minutes	N/A^
	Snowstorm ("Lake Effect")	48 hours	~96 hours

note that, although emergency services in Germany had a good grasp of forecast uncertainty, it was not possible to identify a particular probability threshold at which mitigation measures would begin. However, it was noted that decisions were delayed for low probabilities. Studies suggest that the general public often misunderstand the nature of the hazard from severe weather events; for example, Meyer et al. (2014) found that residents of coastal regions in the United States typically overestimated the probability of their homes being hit by hurricane-force winds, but underestimated the damage that such winds could cause. They also erroneously perceived the greatest threat to come from the wind rather than the storm surge. Since the public response to weather warnings is a key element in their success, determining warning quality necessarily takes forecast verification beyond the traditional quantitative forecast skill measures used so far into the arena of social sciences; for example, the Met Office in the United Kingdom utilises the subjective analysis of data from social media posts among other sources to try to assess the quality of warnings.

3.7.4 Impacts

3.7.4.1 Human impact

Direct effects occur during the impact phase of a windstorm, causing death and injury as a result of the force of the wind, and the main dangers include becoming airborne, being struck by flying debris or falling trees and road traffic accidents. Indirect effects, occurring during the pre- and post-impact phases of the storm, include falls, lacerations and puncture wounds, and occur when preparing for, or cleaning up after, a storm. Power outages are a key issue and can lead to electrocution, fires and burns and carbon monoxide poisoning from gasoline-powered electrical generators. In addition, worsening of chronic illnesses owing to lack of access to medical care or medication can occur. Other health impacts include subsequent infections and an increase in insect bites (Goldman et al., 2013).

Owing to their large scale, severe extra-tropical cyclones can expose a very large number of people to hazards, such as injury and loss of life, as can tropical cyclones if landfall is made in densely populated areas.

Severe winds from convective storms have a highly localised and short-lived nature, which means that they frequently occur without any consequence for human health. However, when they occur in certain circumstances they can have severe consequences: for example, an outbreak of convective cells caused downbursts of 29-37 m/s to strike the Pukkelpop music festival in Belgium (18 August 2011), exposing 60 000 people to the associated hazard for approximately 10 minutes. Five people were killed, at least 140 were injured as a concert tent collapsed, and trees, light towers and video screens were blown over. Nearby residences were, however, completely unaffected by the event (De Meutter et al., 2015). Intense long-lived tornadoes (as occur in the United States) can potentially expose a large number of people to hazards due to flying debris. In Europe, tornadoes are generally weaker and much shorter lived than those experienced in the United States; however, it has been estimated that in Europe there are 10-15 tornado-related deaths per year (Groenemeijer and Kühne, 2014).

Storms can lead to a range of direct and indirect impacts on people and on the built and natural environment.

Lightning presents a hazard to humans and infrastructure systems as well as being a major cause of wildfires. Annually, there are approximately three deaths by lightning strike per 10 million of the population in developed countries (Lorenz, 2008; Holle, 2008) and perhaps as many as 60 deaths per 10 million of the population in the developing world (Holle, 2008). These differences are due to the shift in demographics of developed nations from a largely rural population involved in agricultural work to an urban population spending significantly more time indoors, and to the fact that buildings in developed countries mostly now contain conducting elements, such as electrical wiring, telephone cables, or purpose-built lightning conductors, which provide safe charge transfer paths to ground. For example, the risk of death from lightning strike in the United Kingdom has reduced by about 95 % over the past century (Elsom, 2015), and data from Elsom and Webb (2014) indicate that changes in the nature of buildings reduced the proportion of fatal lightning strikes that occurred indoors from 32 % in the 1850s, to 5 % in 1950s, to 0 % during the most recent period (1988-2012). Reductions of a similar order of magnitude have been reported in other developed countries (Holle et al., 2005), but not in developing countries, where the risk of death remains greater (Holle, 2016).

Thunderstorm asthma is a term used to describe an observed increase in acute bronchospasm cases following severe thunderstorms. These asthma events have had significant impacts on both individuals and health services, with a range of different aeroallergens identified (Dabrera et al., 2013). The impact of these rare events can be significant, with many without previous asthma events becoming acutely ill (Murray et al., 1994). Health services can be seriously affected by thunderstorm asthma; for example, during the 24/25 June 1994 thunderstorm asthma episode, hospital emergency departments ran out of asthma-related supplies including nebuliser face masks (5 of 11 departments) and drug therapies (8 of 11) and half of all the regional health authorities in England observed a 6-fold increase in asthma attendances in emergency departments, resulting in difficulty in service provision (Venables et al., 1997).

Large hail has the potential to produce significant head trauma and in extreme cases can result in death. Such extreme cases with multiple deaths have been reported particularly in northern India, Bangladesh and parts of China, but the details of these are difficult to verify. In the United States, only eight deaths from hail were reported in the 70 years prior to 2009 (Changnon et al., 2009), although larger numbers of non-fatal injuries are reported. To the authors' knowledge, there have been no reported deaths as a direct result of being struck by hail in Europe in recent decades, despite the occurrence of damaging hailstorms such as that in Munich in 1984 (Heimann and Kure, 1985); however, hail has been a contributing factor in fatal traffic accidents.

3.7.4.2 Infrastructure and environment

Damage from high winds associated with extra-tropical cyclones varies according to the wind gust to the power of 3 (or more), so prediction of the correct values is crucial (but still very challenging). This rapid increase in vulnerability with wind strength relates to building regulations that specify resilience to certain standards (e.g. in the United Kingdom and in Eurocodes, 50-year return periods are quoted for some purposes). As winds nominally increase above such thresholds, the building 'failure rate' will naturally accelerate rapidly.

Damage to property and crops from hail storms can be very costly: for example, the Munich hailstorm of 1984 (hail diameter 5-6 cm) caused significant damage to vegetation, buildings, automobiles and aircraft, leading to USD 500 million (equivalent to USD 1.2 billion -EUR 1.1 billion- today) of insured losses (Heimann and Kurz, 1985). A more recent hailstorm in Germany in July 2013 caused damage worth USD 5 billion (equivalent to USD 5.2 billion -EUR 4.8 billion- today), part of the explanation for the increase in potential losses being increased use of 'expensive construction materials and complex building façades' (MunichRe, 2016).

Regarding damage to environment, more than 130 separate wind storms have been identified as causing noticeable damage to European forests in the last 60 years (~2/year) that, for example, increases the vulnerability of forests to wildfires (see Chapter 3.10). Storms are responsible for more than 50 % of all primary abiotic and biotic damage by volume to European forests from catastrophic events (Gardiner et al., 2011; De Rigo et al.; 2016).

3.7.5 Conclusions and key messages

Partnership

Collaboration between forecast providers and end users in real time is essential during DRM, since the interpretation of the available information, the uncertainty associated with it and how this changes as new information becomes available should be made in consultation with qualified meteorologists and National Meteorological Services in particular. Information sharing, particularly observational, impact and warning data across national boundaries in real time, is of key importance. Improvements in forecasts will in part be driven by the interaction between fundamental atmosphere and ocean science with operational forecasting, so continued collaboration between forecasting centres and universities and research centres is crucial.

Knowledge

A greater understanding of how to interpret, utilise and communicate probabilistic forecasts is required. This is particularly important, since future developments in forecasting systems, particularly short-lead-time, high-resolution forecasts at small spatial scales and long-lead-time global forecasts, lead to forecasts that are inherently probabilistic. Collaboration between physical scientists and social scientists may be important to improve the communication of forecast probabilities.

Innovation

Prospects for major extensions of the lead-time thresholds at which we can forecast storms are limited. We should instead expect continued slow but steady extensions of these over the coming years and decades. Improvements in the quality of forecast information for end users will also stem from innovative and improved post-processing of forecast data for the diagnosis of hazardous weather and end user-specific information.

3.8 Meteorological risk: extreme temperatures

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3.8.1 Temperature extremes in a disaster risk management context

Understanding temperature extremes in a DRM context involves getting to know how often temperature extremes occur, the conditions under which they occur and establishing associated direct and indirect societal impacts.

Knowledge about temperature extremes can inform the development of strategies for managing the risk associated with this type of natural event. That temperature extremes do result in disastrous consequences, in terms of lives lost, is manifest via the observed impacts of a range of extreme temperature events over the last few decades (Table 3.3). Noteworthy is that all top 10 disasters are related to extreme high as opposed to low temperatures.

Temperature extremes, although rare, are important from a DRM perspective as they can lead to a range of substantive direct and indirect impacts on human activity and other systems.

3.8.2 What are temperature extremes?

Temperature extremes can occur over a range of temporal (e.g. daily, monthly, seasonal, annual, decadal) and geographical scales (e.g. local to regional to global). They are usually defined in terms of their position in a distribution of observed temperature values or as a threshold value recorded at a meteorological or climate station.

Temperature extremes can be expressed as a probability of occurrence, or as a return period (e.g. 5 % probability or 1 in 20 year return period). Occasionally, the term 'return period' is misinterpreted to mean an event of a particular magnitude, so that an event with a return period of 1 in 20 years, having once occurred, will occur again only after 20 years have passed. This is incorrect, as at any one time the occurrence of a particular temperature will have a specific probability associated with it. Given this, it is entirely possible to have two 1 in 20 year events in successive years or indeed in the same year.

A threshold value will be a specific high or low temperature value, above or below which there is a discernible impact. These can be described in terms of percentiles, for example, the 5th or 95th percentile, meaning that for all the temperature observations recorded for a location, the highest or lowest set of temperatures are considered to fall within the lowest or highest 5 % of values. Percentiles are a relative measure of extreme values, as the value associated with a particular percentile will vary from location to location. For example, the 95th percentile value of temperature for a location in southern Europe may be 35°C, while for a northern European location it may be 28°C.

Probabilities, return periods and percentiles are just a few of a wide range of possible measures of temperatures extremes. For example, Table 3.4 lists a set of measures of temperature extremes considered relevant to a range of sectors of the economy and society (Donat et al., 2013). Among these are some that refer to the duration of high or low temperatures over several days. These are often referred to as heat waves or cold waves. Although these terms are applied extensively in a range of fora, there is no standard definition of what a heat wave or cold wave is, despite a number of attempts to develop 'universal' heat wave and cold wave definitions (Allen and Sheridan, 2016; Lhotka and Kysely, 2015; Perkins and Alexander, 2013; Robinson, 2001; Tong et al., 2010).

Building a picture of the nature of temperature extremes for a particular location or region is dependent on measurements from daily weather and climate observing stations. Accordingly, a number of daily temperature datasets that can be used for risk analysis have been constructed based on available station data (Klok and Tank, 2009; Menne et al., 2012).

There is a range of temperature extreme metrics. Statistical measures including probabilities, return periods and percentiles can be used to describe their occurrence. Knowledge gaps exist concerning extreme urban temperatures.

TABLE 3.3

Top 10 extreme temperature disasters and associated death toll by country and date.
Source: EM-DAT (2009)

Country	Disaster type	Date	Total number of deaths
Russian Federation	Extreme high temperature	01/06/2010	55 736
Italy	Extreme high temperature	16/07/2003	20 089
France	Extreme high temperature	01/08/2003	19 490
Spain	Extreme high temperature	01/08/2003	15 090
Germany	Extreme high temperature	01/08/2003	9 355
France	Extreme high temperature	29/06/2015	3 275
Portugal	Extreme high temperature	01/08/2003	2 696
India	Extreme high temperature	26/05/1998	2 541
India	Extreme high temperature	20/05/2015	2 248

In addition to observational data, other sources are increasingly being used to develop extreme temperature climatologies (e.g. assembled via data rescue and reconstruction projects, as well as the analysis of diaries and other historical documents (McGregor, 2015)). Considerable effort has also gone into constructing gridded temperature datasets with a variety of spatial and temporal resolutions (Donat et al., 2013). In the case of data-sparse regions, stochastic weather generators have also been applied to the analysis of temperature extremes (Rahmani et al., 2016; Steinschneider and Brown, 2013; Wilks, 2012). A range of reanalysis products such as the 20th century (100-year) reanalysis dataset produced by the ECMWF (ERA-20C, n.d.) also offer considerable potential for extreme temperature analyses. Because weather and climate stations were originally located to be representative of atmospheric processes over large regions, there are very few long-term urban weather stations. This has constrained the development of a full understanding of the complexities of urban temperature fields and associated extremes (Chen et al., 2012).

Accordingly, attention is now being turned to the development of urban climate networks and information systems (Chapman et al., 2015; Choi et al., 2013; Honjo et al., 2015; Hu et al., 2016; Muller et al., 2013a, b). Furthermore, satellite-based high spatial

TABLE 3.4

List of the temperature indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) and calculated based on Global Historical Climatology Network (GHCN)-Daily station data. Percentile values used as the threshold for some of the indices are calculated for the base period 1961-90.
Source: adopted from Donat et al. (2013)

Identifier	Indicator name	Indicator definition	Units
TXx	Hottest day	Monthly maximum value of daily maximum temperature	°C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	°C
TXn	Coldest day	Monthly minimum value of daily maximum temperature	°C
TNn	Coldest night	Monthly minimum value of daily minimum temperature	°C
TN10p	Cool nights	Percentage of time when daily minimum temperature < 10th percentile	%
TX10p	Cool days	Percentage of time when daily maximum temperature < 10th percentile	%
TN90p	Warm nights	Percentage of time when daily minimum temperature > 90th percentile	%
TX90p	Warm days	Percentage of time when daily maximum temperature > 90th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between daily maximum and minimum temperature	°C
GSL	Growing season length	Annual (1 January to 31 December in NH, 1 July to 30 June in SH) count between first span of at least 6 days with TG > 5°C and first span after 1 July (1 January in SH) of 6 days with TG < 5°C. (NH stands for Northern Hemisphere, SH for Southern Hemisphere and TG is daily mean temperature)	Days
ID	Ice days	Annual count when daily maximum temperature < 0°C	Days
FD	Frost days	Annual count when daily minimum temperature < 0°C	Days
SU	Summer days	Annual count when daily maximum temperature > 25°C	Days
TR	Tropical nights	Annual count when daily minimum temperature > 20°C	Days
WSDI	Warm spell duration index	Annual count when at least 6 consecutive days of maximum temperature > 90th percentile	Days
CSDI	Cold spell duration index	Annual count when at least 6 consecutive days of minimum temperature < 10th percentile	Days

resolution surface temperature observations are also being applied in the analysis of urban surface temperature fields (Azevedo et al., 2016; Hu et al., 2015; Jin, 2012) as well as the output from urban climate numerical models (Best and Grimmond, 2015; Loridan and Grimmond, 2012).

3.8.3 Climatic variability and change and temperature extremes

Climatic variability refers to variations in climate conditions from time period to time period (e.g. intra-seasonal, inter-annual, inter-decadal). In general, climatic variability is connected with variations in the state of the atmospheric and ocean circulation and land surface properties (e.g. soil moisture) at the intra-seasonal to inter-decadal timescales. Climate change in contrast refers to a systematic change in the statistical properties of climate (e.g. mean and standard deviation, etc.) over a prolonged period (e.g. several centuries) as manifested by an upward or downward trend in, for example, extreme temperature values. For the majority of the Earth's climate history, systematic changes in climate have occurred because of natural causes, such as variations in the nature of the Earth's orbit around the sun or solar output. However, there is now mounting evidence that humans are an important climate agent.

Weather experienced at the surface of the Earth is very much influenced by the atmospheric circulation and the pattern of air and moisture flow above a location or region. Many extreme temperature events can therefore be explained in terms of unusual patterns of atmospheric circulation, such as 'blocking', which the term given to a situation in which a high-pressure system becomes 'stuck' and does not move for several days. Blocking results in the flow of either very warm or cold air over a region or cloudless skies that enhance heat gain or heat loss from the Earth's surface. For example, Della-Marta et al. (2007) have shown that heat waves over Europe are related to persistent and large-scale high-pressure systems.

Unusual atmospheric circulation patterns, which are often related to major modes of climatic variability, spawn extreme temperature events. There is mounting evidence that human-related climate change is affecting extreme temperature occurrence.

Alterations to the usual pattern of atmospheric circulation and thus the occurrence of blocking and associated extreme temperature events can often be traced back to interactions between the ocean and atmosphere or modes of climatic variability, such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Donat et al., 2014; Hoy et al., 2013; Scaife et al., 2008). For example, there is evidence that extreme maximum temperatures can be significantly influenced by ENSO for a range of regions across the world (Arblaster and Alexander, 2012; Kenyon and Hegerl, 2008; Parker et al., 2014) as well as by Madden–Julian Oscillation-related anomalies in tropical convection (Cassou et al., 2005; Matsueda and Takaya, 2015). Similarly, the NAO has been found to influence the occurrence of both high- and low-temperature extremes across Europe (Burgess and Klingman, 2015; Hoy et al., 2013; Kenyon and Hegerl, 2008; Moore and Renfrew, 2012; Scaiffe et al., 2008). Changes in the position of the Inter-Tropic Convergence Zone also seem to alter the possibility of temperature extremes in France and Egypt (Boe et al., 2010).

The IPCC has concluded that there is unequivocal evidence that humans, through a range of activities and an intensification of the greenhouse effect, are having an impact on the Earth's climate (IPCC, 2013). This is most evident through an increase of the global mean temperature of about 0.8°C since 1880, with two-thirds of that increase occurring since 1975, at a rate of roughly 0.15-0.20°C per decade (NASA, 2016). Understandably, this observed increase and that projected for the next several decades has implications for the occurrence of high- and low-temperature extremes (Russo et al., 2014; Seneviratne et al., 2012). That changing global temperatures appear to be already manifesting themselves in an altered occurrence of temperature extremes and heat and cold waves are evident at a range of geographical scales (Fischer, 2014; Schar, 2016). Furthermore, there is emerging evidence that a number of recent extreme temperature events are in part attributable to human-related changes in global temperatures (Easterling et al., 2016, Kim et al., 2015; Mitchell et al., 2016).

3.8.4 Health impacts of temperature extremes

Both high and low temperatures, indoors and outdoors, pose substantial risks to human health, including increases in mortality, morbidity and health service use (Ryti et al., 2016; WMO, 2015). In many countries, the health impacts of cold temperatures substantially outweigh those of heat (Gasparrini et al., 2015).

The scale and nature of the health impacts observed depends on the timing, intensity and duration of the temperature event, the level of acclimatisation and adaptation of the local population, infrastructure and institutions to the prevailing climate, as well as the definitions and methodologies used for scientific research. As such, the health effects of temperature extremes and the determinants of vulnerability are, to some extent, context specific.

Population health impacts start to be observed at winter and summer temperatures that are considered moderate for the season and then increase as temperatures become more extreme, in what is variously described as a U-, V- or J-shaped curve. The precise threshold temperatures for health impacts vary by region and country, as does the scale of the health impacts by degree change in temperature, but the overall pattern remains similar wherever it has been studied.

For both heat and cold, the impact of temperature is more marked for deaths than for hospitalisations (Hajat et al., 2016; Linares and Diaz, 2008); this may suggest that individuals die before they reach health care. Temperature extremes may also result in illness that is not sufficiently severe to require hospital attention and that has not been captured by these studies.

For heat, deaths and hospitalisations occur extremely rapidly (same day) and they may be followed by a degree of impact displacement (health impacts in the frail brought forward), which returns to normal within a matter of days (Basu, 2009). The onset of health impacts for cold are slower and persist for longer (up to 4 weeks), with short-term displacement effects not apparent (Analitis et al., 2008).

The health impacts of temperature extremes, which can be direct or indirect, are moderated by a range of social determinants, which can be broadly referred to as vulnerability and resilience.

Longer heat events are associated with greater health effects because of the longer period of exposure (D'Ippoliti et al., 2010), but this has not been consistently observed for cold (Ryti et al., 2016).

Severe heat events that occur towards the beginning of a season have greater health impacts; this is likely to be partly due to loss of the most vulnerable members of the population during the first episode and partly due to population adaptation for subsequent events (Baccini et al., 2008). This pattern is less clear for severe cold, with some authors indicating that cold weather events towards the end of the season are associated with greater mortality (Montero et al., 2010a).

There is some evidence that there has been a reduction in health effects from heat extremes over recent years in some countries, which suggests that there has been some individual and institutional adaptation (Arbuthnott et al., 2016). This is less well established for cold risks.

3.8.4.1 Health impacts

Health impacts may be direct (caused by the direct effect of the hazard) or indirect (caused by the consequences of the hazard such as changes in behaviour or impact on services), as shown in detail in Table 3.5.

a) Direct impacts

As the ambient temperature changes, the human body's physiology adapts in order to maintain a stable body temperature. This includes changes to the circulatory, respiratory and nervous systems to allow cooling or to protect vital organs (Ryti et al., 2016; WMO, 2015).

Direct health impacts occur when a stable body temperature cannot be

TABLE 3.5

Direct and indirect health impacts of temperature extremes

Health impacts	Heat	Cold
Direct	Increased risk of classical heat illness: • dehydration • heat cramps • heat exhaustion • heat stroke Increased risk of death from: • respiratory disease • cardiovascular disease • other chronic disease (e.g. mental health conditions and renal disease) Increased risk of hospitalisation particularly from: • respiratory disease • diabetes mellitus • renal disease • stroke • mental health conditions Increased risk of poor outcomes in pregnancy	Increased risk of classical cold illness: • hypothermia • frostbite Increased risk of death from: • cardiovascular disease • respiratory disease • other chronic diseases (e.g. stroke and dementia) Increased risk of hospitalisation particularly from: • respiratory disease • cardiovascular disease • stroke Increased risk of poor outcomes in pregnancyy
Indirect	Impact on health services including: • increased ambulance call-outs and slower • response times • increased numbers of emergency department attendances • increased number of hospital admissions • storage of medicines Increased risk of accidents: • drowning • work-related accidents • injuries and poisonings Increased risk of: • outbreaks of gastrointestinal disease • marine algal blooms Potential disruption to infrastructure: • power • water • transport • productivity	Impact on health services including: • increased ambulance call-outs and slower response times • increased numbers of emergency department attendances • increased number of hospital admissions Increased risk of accidents: • injuries from falls • traffic accidents • carbon monoxide poisonings Increased risk of: • outbreaks of gastrointestinal disease • social isolation Potential disruption to infrastructure: • power • water • transport

maintained (e.g. when temperatures are too extreme), when clothing or shelter is not suitable or when physiological responses are impaired (e.g. through disease, normal ageing or using certain medications). Moreover, these impacts may be exacerbated when other demands are placed on the body, such as strenuous activity or drug/alcohol use. This produces classical temperature-related disease, such as hypothermia and heat stroke, both of which may have a rapid onset, may not be quickly identified and may be fatal.

However, classical hypothermia and heat stroke are not the major cause of health impacts from temperature extremes; most temperature-related deaths and illness are from chronic diseases such as heart and lung disease (Bunker et al., 2016), which form an important proportion of the background disease burden in European populations. This is because an already impaired physiological system is less able to adapt to the ambient temperature, and the physiological changes needed to regulate temperature may worsen pre-existing disease.

b) Indirect impacts

Temperature extremes also have indirect impacts on health, for example through impacts on services or changes in individual behaviour as a result of the temperature.

The impact on health services may be mediated through increasing demand for care, direct and indirect impacts on staff, which affect their ability to work, or ambulance response times (Thornes et al., 2014). Temperatures extremes may have impacts on wider infrastructure that is essential for health, such as power, water and transport (USAID, 2013).

Behavioural changes may have inadvertent negative health consequences, replacing one risk with another, which is an important explanation for the increase in injuries associated with hot and cold weather (Bulajic-Kopjar, 2000; Otte et al., 2016).

3.8.4.2 Determinants of vulnerability

The major determinants of vulnerability of a population to temperature extremes relate to the features of the population exposed and their capacity to respond and adapt to the temperature conditions over long and short time frames. Determinants of vulnerability can be broadly categorised by demographic, health, physical, socioeconomic and institutional factors, many of which are inter-related and dynamic.

Temperature extremes rarely occur in isolation and related hazards such as snow/ice, drought/wildfires, poor air quality or other unrelated disasters may coincide in time and geography. Responses to these additional hazards may alter existing vulnerabilities and the capacity to adapt to temperature extremes.

a) Demographic determinants

The physiology of older people and the very young renders them more vulnerable to temperature extremes. They may also be less able to adapt their behaviours or environmental conditions and may be more dependent on others (Collins, 1986; Hansen et al., 2011). New migrants or tourists may not understand warnings or how to seek help. Some studies have suggested increased risk by gender (female) and race (black and minority ethnic groups) but this may be explained by alternative factors such as age, income, education, underlying disease and access to health care.

b) Health status determinants

Many physical and mental health conditions increase vulnerability to adverse temperatures through a direct effect on the body's physiology or through the effect of certain medications (Hajat et al., 2007). People with poor health or disability may be less aware of warnings, may be less able to adapt their behaviours or environmental conditions, and may be more dependent on others.

c) Physical determinants

People spend approximately 80 % of their time indoors, with the elderly or unwell spending longer periods indoors. Buildings (including homes, hospitals, schools and prisons) are not always adapted for temperature extremes and may have insufficient heating/energy efficiency or cooling measures (Conlon et al., 2011; Hansen et al., 2011).

People who have inadequate shelter (e.g. displaced or homeless populations) might be particularly exposed to temperature extremes and often have associated vulnerabilities such as poor health or economic circumstances.

d) Socioeconomic determinants

People who are socially isolated are more at risk from temperature extremes because they are less able to access community support, and may also have additional health or other vulnerabilities (Bouchama et al., 2007; Tod et al., 2012).

Low-income groups may be less able to adapt to their behaviours or environment. Certain occupational groups, such as labourers, may not always be afforded adequate protection from temperature extremes (e.g. undertaking strenuous physical work during very hot periods) (Hanna et al., 2011).

e) Behavioural/cultural determinants

When temperatures become more extreme, most people take some action to adapt to the conditions. However, some factors limit the ability to adapt, such as age, poor health or economic circumstances, and certain belief or value systems may also mean that appropriate action is not taken in response to the temperature conditions (Hansen et al., 2011; Tod et al., 2012). Certain behaviours, intended to be protective, may inadvertently increase health risks (e.g. swimming in unsupervised open waters (Fralick et al., 2013), shovelling snow (Franklin et al., 1996) or using unsafe heating appliances (Ghosh et al., 2016)).

f) Institutional determinants

Health services need robust plans in order to manage the potential disruption and increased demand during and following temperature extremes; their ability to respond influences population vulnerability. This also applies to supporting infrastructure such as power, water, communication and transport systems. Mass gatherings can place additional strains on services, especially if they coincide with temperature extremes (Soomaroo and Murray, 2012).

Employers should take action to ensure that employees are able to take necessary protective actions, such as increasing fluid intake, having access to adequate rest and shade and restricting strenuous activity to cooler parts of the day.

Many countries have formal plans and policies that promote actions to reduce the risk of temperature extremes, such as the Heatwave and Cold Weather Plans for England (see Chapter 3.8.6.2).

3.8.5 Other impacts of temperature extremes

To date, the human health impacts of high and low temperatures have received a great deal of attention in both the academic and technical literature related to DRM compared with 'other' impacts. In general, 'other' direct and indirect impacts tend to be less well understood than those related to human health. This, however, does not make them less important, as heat- or cold-related impacts may lead to complex disasters, for example those that may arise from the malfunction of energy supply systems, which may lead to the failure of the critical infrastructure necessary to maintain a range of human activity systems and, most importantly, the emergency services. A summary of other impacts arising from low- and high-temperature extremes is given below:

It has been documented that both high and low temperatures have significant effects on plants (Barlow et al., 2015).

Extreme heat stress can reduce plant photosynthetic and transpiration efficiencies and negatively impact plant root development, which acts collectively to reduce the yield of crops. In general, extreme high temperatures during the reproductive stage will affect pollen viability, fertilisation and grain or fruit formation (Hatfield and Prueger, 2015).

Late frosts are particularly damaging to the opening buds of plants. More economic losses in the United States are caused by crops freezing than by any other weather hazard (Snyder and Melo-Abreu, 2005). Even a single night with unusually low temperatures can lead to significant ecological and economic damage (Inouye, 2000). Because of climate change, many plants are now coming out of winter dormancy earlier (Walther et al., 2002), which leaves them even more susceptible to frost damage. Frosts can have lasting effects, as they can cause local extinctions and influence the geographical distribution of some species (Inouye, 2000).

Livestock, such as rabbits, pigs and poultry, are vulnerable to extreme temperatures. Milk production and cattle reproduction decreases during heat waves, and millions of birds have been lost as a result of such events. In extreme cold weather, livestock are also at risk if not protected from the cold (Adams, 1997).

It is a concern that non-health impacts of temperature extremes are not entirely understood, as in combination they possess the potential to create complex disasters and, thus, to have far-reaching societal impacts.

Air quality is impacted by both heat waves and low-temperature events. Increased ozone pollution is associated with high temperatures, and nitrogen oxides, SO2 and particulate matter pollution is associated with low temperatures (Hou and Wu, 2016). Heat waves also affect water quality, bringing an increased risk of algal blooms, causing the death of fish in rivers and lakes and the death of other organisms in the water ecosystem (Adams, 1997).

Heat waves can directly impact ecosystems by constraining carbon and nitrogen cycling and reducing water availability, with the result of potentially decreasing production or even causing species mortality. Extreme temperature conditions can shift forest ecosystems from being a net carbon sink to being a net carbon source (IPCC, 2012).

The effects of both high and low temperatures can be exacerbated if combined with water shortages, leading to drought (for a detailed discussion, see Chapter 3.9).

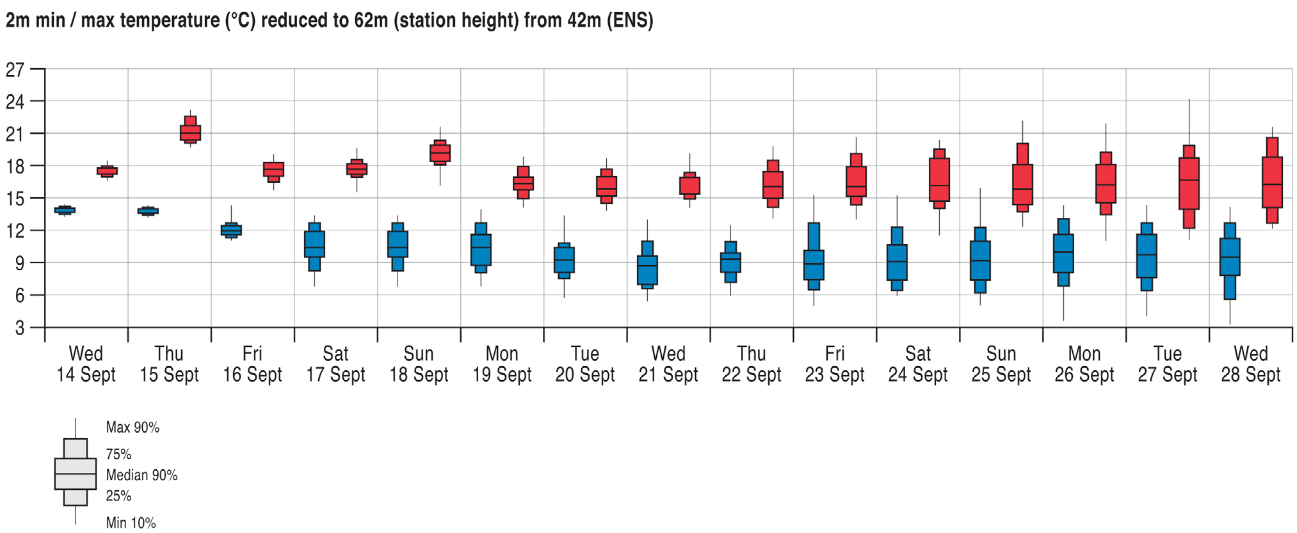
3.8.6 Managing temperature extremes

3.8.6.1 Forecasting

Forecasting extreme temperatures on the medium (more than 3 days) to seasonal (up to 6 month) scale is an important tool for civil protection

FIGURE 3.29

Ensemble forecast for maximum and minimum temperature in Durham, United Kingdom, issued on 14/09/2016, 00 UTC (Coordinated Universal Time). The figure illustrates the maximum and minimum daily temperature for each day, shown as a box plot, giving a range of possible maximum and minimum temperatures and, therefore, the uncertainty in the forecast; the further ahead a forecast is issued, the more uncertain it becomes.
Source: courtesy of authors



(Mayes, 2012; Ilkka et al., 2012).

However, forecasts on this timescale are uncertain and, therefore, multiple scenarios, known as ensembles, are used. Figure 3.29 shows such a forecast for 15 days for the city of Durham (United Kingdom). This plot clearly shows that the further ahead a forecast is issued, the more uncertain it becomes, with a range of possible values. This poses a challenge for forecasting heat and cold waves beyond the medium timescale.

Heat and cold wave predictability is also linked to a forecast model's ability to predict transitions between circulation patterns such as blocking and phases of modes of climatic variability such as ENSO and the NAO, as described in Chapter 3.8.3. Because of their low-frequency nature and their teleconnections, modes of climatic variability can exhibit predictability on the subseasonal timescale. A further source of predictability also arises from the effect of soil moisture conditions in the amplification of the temperature anomalies (Quesada et al., 2012). Therefore, accurate skill in predicting persistent large-scale high-pressure systems is fundamental to forecasting heat and cold waves.

The ideal method by which to eval-

FIGURE 3.30

2-metre temperature composites from ERA-Interim weekly mean anomalies for heat wave events: western Europe (left), northern Europe (centre) and Russia (right).
Source: courtesy of authors

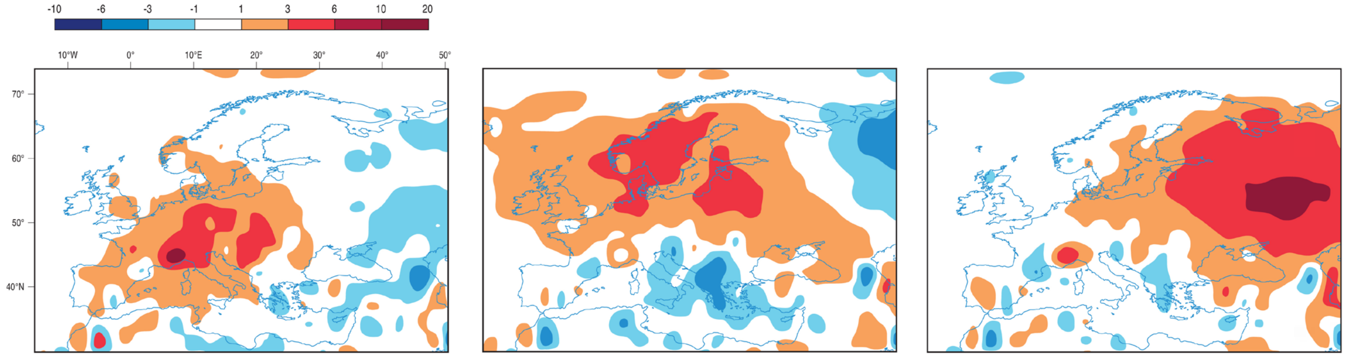
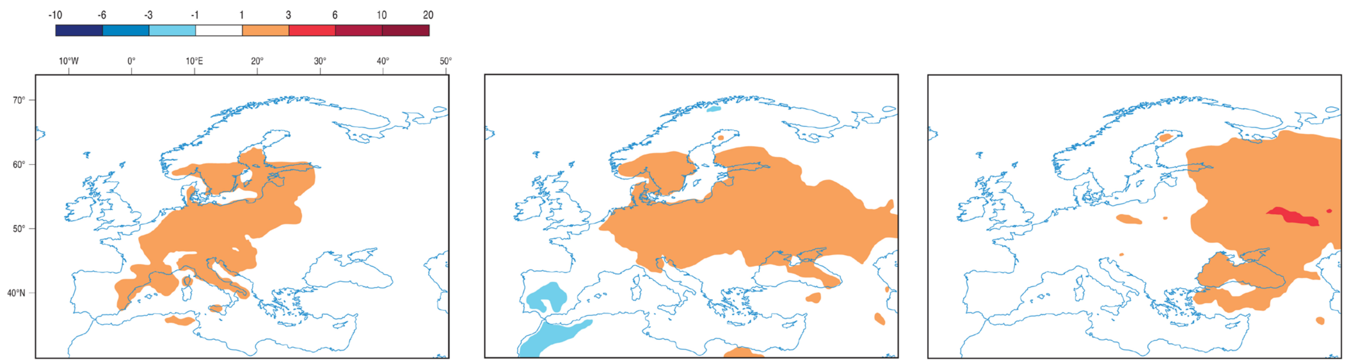


FIGURE 3.31

2-metre temperature composites from the ensembles forecast at 12-18 days verifying the same events as in Figure 3.30. Western Europe (left), northern Europe (centre) and Russia (right).
Source: courtesy of authors

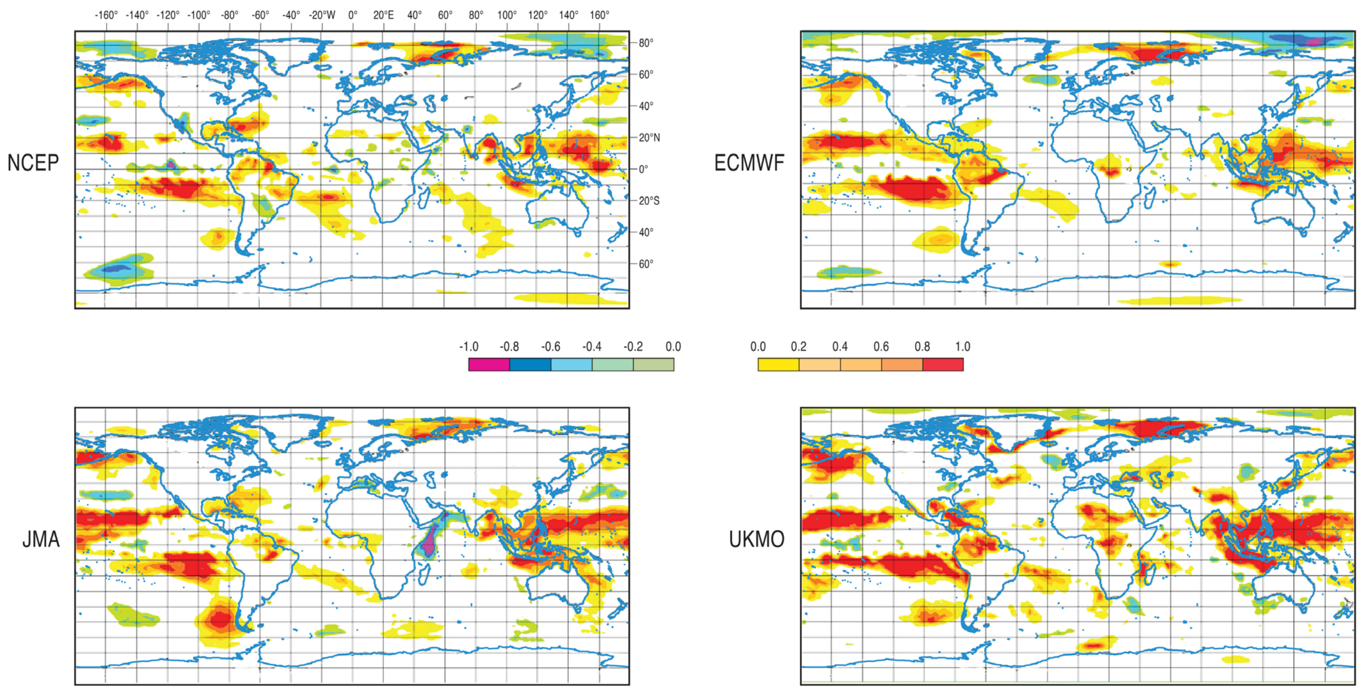


uate the skill of an extended range ensemble in predicting heat and cold waves is to use a selection of objective verification measures for probabilistic forecasts. In reality, verification requires a far larger sample than is available. This is typically the case for any investigation that involves extreme events. Here we show the evaluation of individual heat waves, as shown in Figure 3.30, as an example. The 2-metre temperature composites, based on weekly mean anomalies of ensembles forecasts at 12-18 days, are shown in Figure 3.31. Compared with the observations (Figure 3.30), the forecasts (Figure 3.31) generally identify the location of warm anomalies with a certain degree of accuracy, although the amplitude is underestimated. Overall, the successful predictions reflect a persistent anti-cyclonic circulation already present in the initial conditions. This testifies to the critical nature of an extended-range forecast model to represent transitions to anti-cyclonic circulation regimes, which is consistent with the cause of so-called medium-range forecast 'busts' (Rodwell et al., 2013).

Careful calibration and judicious combination of ensembles of forecasts from different models into a larger ensemble can give greater accuracy than is obtained from any single model. However, comparing, verifying and testing multimodel combinations from these forecasts and quantifying their uncertainty as well as the handling of such a massive dataset is challenging and is the subject of the ECMWF subseasonal to seasonal (S2S) prediction project. This is a WWRP/THORPEX-WCRP joint research project established to improve fore-

FIGURE 3.32

Extreme Forecast Index of 2-metre temperature with a forecast range of 12-18 days verifying the week of 8-14 August 2016. Four different forecast systems are shown. Blue areas indicate a cold spell, while red areas indicate a heat wave (on a weekly average). Ncep is National Centre for Environmental Prediction, ECMWF is the European Centre for Medium Range Weather Forecasting, JMA is Japan Meteorological Agency, UKMO is the United Kingdom Meteorological Office.
Source: courtesy of authors



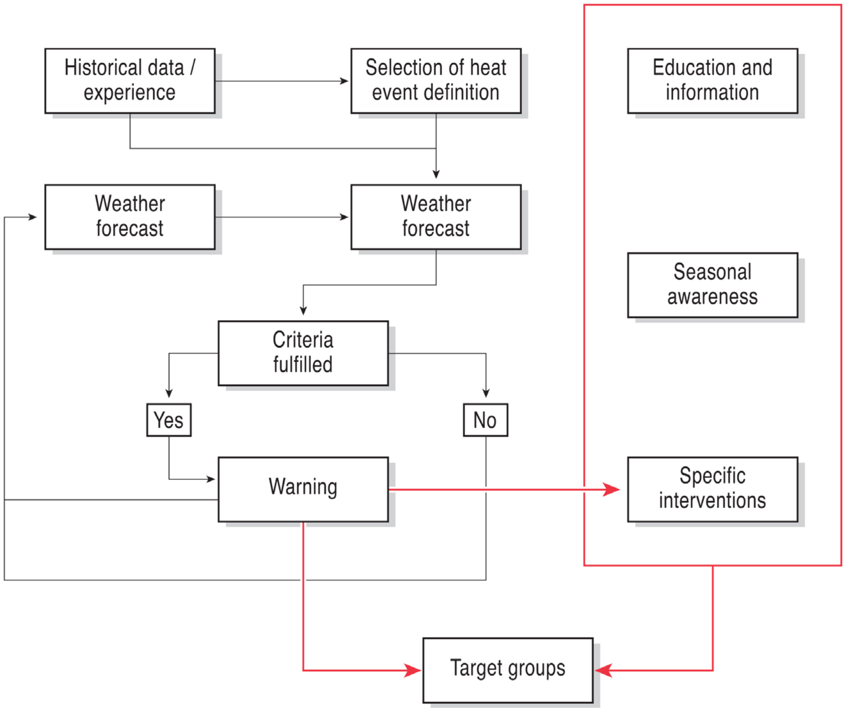
cast skill and understanding on the S2S timescale, and promote uptake of its forecast products by operational centres and the applications community. Examples of some of S2S's products can be found at ECMWF (n.d.). The Extreme Forecast Index (EFI) is one such product (Figure 3.32). This is an integral measure of the difference between the ensemble forecast distribution and the model climate distribution. The EFI takes values from –1 to +1. An EFI of 1 (red) indicates a heat wave, while an EFI of –1 (blue) shows a cold spell. Experience suggests that EFI magnitudes of 0.5-0.8 (irrespective of sign) can be generally regarded as signifying that 'unusual' weather is likely, while magnitudes above 0.8 usually signify that 'very unusual' or extreme weather is likely. Although larger EFI values indicate that an extreme event is more likely, the values do not represent probabilities as such.

3.8.6.2 Early warning systems

Early warning systems have been developed for a number of extreme climate events and are gaining traction in the area of temperature extremes (Carmona et al., 2016; Kalkstein et al., 2011; Kovats and Ebi, 2006; Lowe et al., 2016; McGregor et al., 2015). Such warning systems take the output from short- to medium-range forecasting models (Lowe et al., 2016; McGregor et al., 2006), such as described above, and usually use a threshold temperature or some related index to trigger an alert and/or issue a heat or cold warning (Antics et al., 2013; Nairn and Fawcett, 2015; Pascal et al., 2013). More often than not, a weather- or climate-based EWS for heat or cold, which is composed of a number of components, is nested within a wider heat or cold action plan (WHO, 2008, 2011; WMO, 2015) as shown in Figure 3.33.

FIGURE 3.33

Generic structure of a heat health warning system.
The components in the red box constitute part of a wider heat health action plan. This overall structure can also be applied to cold-related warning systems.
Source: McGregor et al. (2015)



The normative view regarding heat/cold EWSs is that they should deliver discernible benefits for the management of heat- and cold-related risk across a range of sectors (Fouillet et al., 2008). Given this, heat/cold EWSs are increasingly subject to evaluation that can consider EWS processes and/or outcomes, using a variety of criteria. To date, such evaluations indicate that heat/cold EWSs yield discernible benefits in relation to DRM but, notwithstanding this, there is room for improvement, especially as a successful EWS depends heavily on a well-designed set of risk-mitigating and practical intervention strategies being in place (Bassil and Cole, 2010; Chiu et al., 2014; Ebi, 2007; Hajat et al., 2010; Kalkstein et al., 2011; Montero et al., 2010b; Toloo et al., 2013a, b).

For low-temperature extremes, a range of EWS and forecast products have been developed. Many of these are focused on forecasting snow storms (Nakai et al., 2012; Wang et al., 2013) and ice storms, with an emphasis on critical infrastructure such as roads (Berrocal et al., 2010; Degaetano et al., 2008; Palin et al., 2016; Riehm and Nordin, 2012) and power lines (Cerruti and Decker, 2012; Nygaard et al., 2015; Roldsgaard et al., 2015).

Although EWSs are considered a plausible DRM tool, developers and users of EWSs should be aware of some of the generic 'dos and don'ts' of such systems, as outlined by Glantz (2004).

3.8.6.3 Urban design and planning

Cities have received a great deal of attention in the DRM literature because this is where large numbers of people are concentrated; they are, therefore, potentially at risk of heat- and cold-related disasters.

In the case of heat, cities represent a distinct problem because of the so-called urban heat island (UHI) effect which, during periods of high temperatures, can lead to air temperatures in cities being several degrees above those for surrounding rural areas, especially during the nocturnal hours (Arnfield, 2003). This 'extra' heat has the potential to place a large number of vulnerable people in cities at risk of heat-related illness (Wolf and McGregor, 2013; Wolf et al., 2014).

The UHI develops because urban materials are efficient at absorbing and storing heat from the sun during the day and releasing that heat back into the urban atmosphere at night, leading to higher nocturnal temperatures in urban areas than in rural areas. A further factor is the low evaporation rates in cities; evaporation is an energy-consuming and thus a cooling process. Significant quantities of so-called anthropogenic heat from air conditioning systems and vehicles can add to the energy available for raising urban air temperatures (Allen et al., 2011; Offerle et al., 2005; Smith et al., 2009). For example, in London, it has been estimated that approximately 80 % of the anthropogenic heat goes into heating of the atmosphere (Iamarino et al., 2012), with the greatest contributions from London's central activity zone, where the service sector is predominant. Given that large cities, such as London, will grow over the coming decades, anthropogenic heat is likely to become an important heat risk management issue for large cities.

Managing temperature extremes can be approached from a number of perspectives, including using forecasting technology, the development of EWSs and heat/cold action plans and urban design and town planning.

Given the processes that generate the UHI, strategies that focus on managing urban heat can range from the scale of the individual building to the city. Examples include controlling for building material absorption and storage of energy from the sun, ensuring that evaporation is promoted through providing moist surfaces and developing green infrastructure and reducing anthropogenic heat release.

While the specific approaches to managing urban heat are potentially wide ranging (Alexander et al., 2016; Eliasson, 2000; Mills et al., 2010; Phelan et al., 2015), the degree of benefit (the intensity of cooling and improvements to human thermal comfort) arising from urban design- and city planning-related heat mitigation measures (Norton et al., 2015; Sharma et al., 2016; Sun et al., 2016;) depends on considering a multitude of interacting and potentially conflicting factors (Coutts et al., 2013; Hamilton et al., 2014). In addition to the scientific challenges (Chen et al., 2012), the actual mainstreaming of urban climate design and adaptation principles into city planning can sometimes become stalled because of a range of institutional barriers (Lenzholzer and Brown, 2011; Reckien et al., 2014; Ugolini et al., 2015; Uittenbroek et al., 2013; Wolf et al., 2015).

Relatively speaking, urban design for low-temperature extremes has received less attention in the recent DRM literature, no doubt as a result of a perception that, in the near future, heat, as opposed to cold, will pose a greater risk management problem. Interestingly, a consequence of the UHI effect, especially the role of anthropogenic heat, may bring some positive benefits in cities that experience harsh winter climates.

3.8.7 Conclusions and key messages

Partnerships

Cooperation between regional, national and international research communities and climate monitoring agencies and citizen scientists is required to construct internally consistent extreme temperature databases and meaningful sector-relevant extreme temperature metrics. This is particularly the case for urban environments where there is an ever-increasing concentration of people who are potentially at risk from temperature extremes as a result of the urban heat island (UHI) effect. A systematic approach at both national and local levels and across all sectors, involving state, private, voluntary and community actors, is required to understand the wider societal impacts of temperature extremes. Partnerships formed between stakeholders in the risk management of temperature extremes should adopt 'a communities of practice model' in order to develop integrated heat and cold action plans that transcend vulnerability assessment, weather forecasting, intervention strategies, urban design and city planning.

Knowledge

An enhanced understanding of the physical origins of temperature extremes, as well their changing magnitude and frequency, especially in light of climate change, is required. Where possible, historic non-instrument-based temperature records as captured in diaries and other documents could be used to augment the understanding of the climatology of temperature extremes from the local to the regional level. Long-term observational series need to be sustained through the commitment of resources to climate monitoring. Research should be undertaken to improve our understanding of the effectiveness and cost-effectiveness of extreme temperature-related interventions in a variety of different climatic, socio-economic and cultural contexts, with learning shared widely. Conceptual risk models of complex disasters related to temperature extremes are required to scope out agendas for knowledge development.

Innovation

In the absence of observed weather station-based temperature data, the use of weather generators for the creation of temperature time series for extreme value analysis and alternative temperature observation platforms such as satellites in addition to the output from urban climate numerical models should be considered as input into DRM analyses. The idea of drawing on multiple sources of information from data networks, as encapsulated by the concept of 'the internet of things', offers considerable potential for managing disaster risk related to temperature extremes. High-resolution intra-urban mapping of population vulnerability to heat and cold, integrated with information on building type and air and surface temperature, is an innovation that is likely to yield gains for extreme temperature-related DRM.

3.9 Climatological risk: droughts

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3.9.1 Introduction

Drought is one of the most complex and severe weather-related natural disasters and its causes and multi-faceted impacts are often not well understood. Droughts can last from a season to multiple years, and even decades, and cover small watersheds to hundreds of thousands of hectares. In Europe, drought is a recurrent phenomenon, affecting extended areas and large populations annually (Vogt and Somma, 2000). Across the world, millions of people are annually exposed to droughts that seriously affect economic development and environment. While fatalities mainly occur in poor economies, even in more prosperous regions many people die as a result of indirect effects (e.g. Tallaksen and Van Lanen, 2004; WMO and GWP, 2014). In Europe, almost 80 000 excess fatalities as a result of heatwaves (see Chapter 3.8) and forest fires (see Chapter 3.10) associated with droughts were reported over the period 1998-2009 (EEA, 2011).

UNESCO notes that drought can have economic consequences that can go far beyond the immediately impacted areas, such as persistent unemployment and threats to food security, regularly leading to forced migration and social instability (WWAP, 2016). The World Economic Forum (2015) labelled the water crisis as first on the list of factors with a risk of severe impacts for the global community. As one of the reasons for this crisis, drought is likely to become more frequent and severe in the 21st century in many regions of the world, especially in already water-scarce and vulnerable areas, including parts of Europe (IPCC, 2012; 2014).

The key challenge is to move from a reactive society fighting impacts to a pro-active society that is resilient and adapted to the drought risk, for example through the adoption of pro-active risk management (WMO and GWP, 2014; Wilhite et al., 2014). This chapter demonstrates that this requires practitioners, policymakers and scientists to collaborate and use a consistent set of definitions and characteristics. Observed and projected trends in drought as a natural hazard need to be understood.

Drought is a recurrent phenomenon that affects extended areas and large populations, putting societies and the environment at risk in many regions of the world.

The hazard has to be connected to its manifold primary and secondary impacts (e.g. on public water supply, food security, energy production, waterborne transport, health, ecosystems). Current, but also future, societal exposure and context-specific vulnerability must be identified to assess drought risk. If all of these aspects are known, drought risk can be managed through a set of institutional, structural and operational measures, including monitoring and medium-range to seasonal forecasting.

3.9.2 Drought definition and characteristics

From a climatic point of view, a drought results from a shortfall in precipitation over an extended period of time, from the inadequate timing of precipitation relative to the needs of the vegetation cover, or from a negative water balance due to an increased potential evapotranspiration caused by high temperatures. This situation may be exacerbated by strong winds, atmospheric blocking patterns and antecedent conditions in soil moisture, reservoirs and aquifers, for example. Droughts can also be triggered in cold climates by temperature anomalies (Van Loon and Van Lanen, 2012; Van Loon et al., 2014). If this situation leads to an unusual and temporary deficit in water availability, it is called a drought. Droughts are to be distinguished from aridity, a permanent climatic feature, and from water scarcity, a situation in which the climatologically available water resources are insufficient to satisfy long-term average water requirements (e.g. Tallaksen and Van Lanen, 2014).

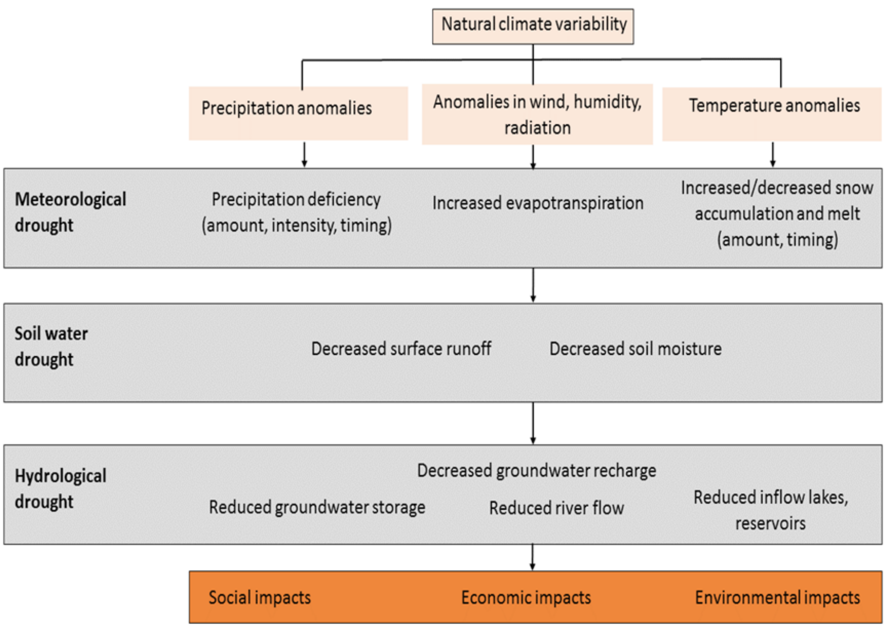
Depending on the prevailing effects on the hydrological system and the resulting impacts on society and environment, drought can be distinguished in terms of meteorological, soil moisture and hydrological factors (groundwater, streamflow, reservoirs) (Figure 3.34 and Box 3.1). The definition of a drought, therefore, will depend on the sector analysed and the related processes and impacts. Finally, the feedbacks between the hydrological cycle and society must be considered (Van Loon et al., 2016). The impacts of drought point to a multitude of drivers that turn lower than average precipitation, limited soil moisture and low water levels into disaster events for vulnerable communities and economies (UNISDR, 2011).

Droughts can be characterised in terms of their onset, duration, severity (accumulated deficit over the entire event) and intensity (total deficit divided by duration).

Standardised indices are used to analyse droughts in different domains of the water cycle (e.g. precipitation, climatic water balance, soil moisture, river flow, groundwater). Among the meteorological indicators, the Standardized Precipitation Index (SPI, McKee et al., 1993) and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) are the most well-known. The SPI is a probabilistic measure of the severity of a dry event (WMO, 2012). It can be calculated for different rainfall accumulation periods (e.g. 1-48 months) and statistically linked to impacts in different economic and environmental sectors. The SPEI has similar characteristics but includes potential evapotranspiration. Recent studies have shown that including the potential evapotranspiration can provide useful drought early warning indicators (McEvoy et al., 2016), al-

FIGURE 3.34

Drought Types: Generating Processes and Impacts
Source: adapted from NDMC and Van Loon (2015)



though some weaknesses occur when the potential evapotranspiration is calculated with temperature-based approaches (e.g. Thornthwaite) in dry, hot regions. Use of SPI and SPEI in cold regions has some limitations, because these indices do not distinguish between rain and snow, which affects the water availability over the year (snow accumulation and melt). Soil moisture-related indicators such as the Soil Moisture-based Drought Severity Index (Cammalleri et al., 2016) or the Palmer Drought Severity Index (Palmer, 1965) aim to characterise the impact on plant water stress; although no specific plant characteristics are included. Hydrological indicators are often based on threshold approaches to quantify the volume of water deficit in rivers and reservoirs (Yevjevich, 1967; Hisdal et al., 2004; Van Loon and Van Lanen, 2012). Finally, combined indicators blend several physical indicators into an indicator of hazard (e.g. US Drought Monitor (Svoboda et al., 2002); Combined Drought Indicator (Sepulcre Canto et al., 2012)).

Drought differs from aridity and water scarcity, and different drought types and associated indices have to be analysed to quantify the multiple drought impacts.

The World Meteorological Organization and Global Water Partnership (2016) have recently published the Handbook of Drought Indicators and Indices, providing structured information on commonly used drought indicators for identifying the spatial extent, onset, duration and severity of drought events. This information supports drought practitioners in selecting appropriate indicators for drought monitoring and early warning as an integral part of risk- based drought management policies and preparedness plans.

3.9.3 Past trends and future projections

Historic trends and future projections of meteorological droughts in Eu-

BOX 3.1

Drought types

Depending on the effect in the hydrological cycle and the impacts on the society and environment, different drought types are commonly distinguished:

Meteorological Drought:
A deficit in precipitation or climatological water balance (i.e. precipitation minus potential evapotranspiration) over a given region and defined period of time with respect to the long-term climatology. It is characterised based on measured and estimated climate variables (e.g. precipitation, temperature, evapotranspiration).

Soil Moisture or Agricultural Drought:
Characterised by reduced soil moisture resulting in a deficit in water supply for agricultural crops and natural vegetation and impacts on crop yield and biomass production. A higher risk for forest fires, due to the accumulation of dry biomass, is another important impact.

Hydrological Drought:
Characterised by reduced streamflows, lake levels, and groundwater reservoirs. Time-series of these variables are used to analyse the occurrence, duration and severity of hydrological droughts that have, for example, impacts on public water supply, energy production and inland water transport.

rope have been investigated by Spinoni et al. (2015a,b, 2016a, 2017) using a combination of indicators based on precipitation and temperature from the E-OBS dataset (Haylock et al., 2008). The analysis considers droughts at seasonal and annual timescales and covers the period 1951-2015 (trend analysis) and 2041-2100 (future projections), the latter of which is based on the EURO-CORDEX multimodel ensemble (Jacob et al., 2014) and moderate (RCP4.5) and extreme (RCP8.5) climate scenarios.

Drought frequency increased in southern and western Europe, but decreased in other parts of Europe. However, an increased frequency is projected, particularly in summer, for most of Europe.

Figure 3.35 demonstrates that in the past six and a half decades northern and eastern Europe experienced a decrease in drought frequency and, less prominently, in drought severity (not shown), while southern and western Europe experienced an increase in drought frequency and severity, particularly over the Mediterranean region (see Hoerling et al., 2012; Gudmundsson and Seneviratne, 2015; Stagge et al., 2016). The noted increase in drought frequency and severity is more widespread when analysing the SPEI, which includes the effect of increasing air temperature on potential evapotranspiration (Spinoni et al., 2015b; Touma et al., 2015; Stagge et al., 2016).

With respect to seasonal droughts, the decrease of drought frequency over northern Europe is more evident in winter, while the increase over southern Europe is more evident in summer.

Figure 3.36 shows that the described past drought tendencies are likely to persist in future decades for the winter months, while in the other seasons – especially summer – the whole of Europe (excluding parts of Iceland and Scandinavia) is projected to experience an increase in drought frequency, in particular during the last decades of the 21st century. At annual scale, and according to both climate scenarios, the drying tendencies over southern and western Europe are projected to become even stronger, with the Mediterranean region being particularly strongly affected (Spinoni et al., 2017; Stagge et al., 2015b). The effects of the projected temperature increase on meteorological droughts are likely to outbalance the effects of the projected precipitation increase over northern Europe and partly over eastern Europe, resulting in more frequent droughts for both scenarios in these territories by the end of the 21st century. The combination of these effects is likely to result in more severe droughts over northern Europe according to the extreme scenario (RCP8.5), while according to moderate scenario (RCP4.5), severity is not likely to increase in this region. The projections are considered to be robust with good agreement between the suite of GCM and RCM models.

At the global scale, past changes in drought frequency and severity are still under debate. Sheffield and Wood (2008) and Sheffield et al. (2012) analysed past global and regional trends using a soil moisture-based drought index for the period 1950-2008. Their results indicate that on a global level only small changes in drought occurrence and extent can be detected over the past 60 years. However, on a regional level, significant drying trends can be seen for parts of the Mediterranean and North, West and Central Africa, as well as for parts of East and Northeast Asia, while in the northern hemisphere and in parts of South America and Australia wetting trends are prevailing. These results are largely confirmed by Spinoni et al. (2014) who analysed meteorological drought frequency, duration and severity over the period 1951-2010. Orlowsky and Seneviratne (2013) investigated future meteorological and soil moisture drought around the world using a multimodel set of CMIP5 simulations. Their results hint towards more frequent soil moisture droughts by the end of the 21st century, especially in South Africa and Central America/Mexico and the Mediterranean. While highlighting the aggravating effect of global warming on droughts, Trenberth et al. (2014) underline the importance of reliable precipitation datasets and the data used to determine the evapotranspiration component in order to avoid conflicting results.

Streamflow drought originates from a temporary deficiency in precipitation and/or from temperature anomalies over a large area that can be further aggravated by other climatic factors, like strong winds or low relative humidity (Tallaksen and Van Lanen, 2004). Long-term precipitation reduction may further aggravate streamflow droughts through the depletion of groundwater and the subsequent decrease in baseflow. In addition, anthropogenic drivers, such as intensive water use and poor water management, can exacerbate low-flow conditions in watersheds, leading to a consequent increase in vulnerability to streamflow drought (Vörösmarty et al., 2000; Döll et al., 2009; Wada et al., 2013).

Trends in historic annual river flow in Europe confirm the patterns in meteorological drought with drying trends in southern and eastern regions of Europe, and generally wetting trends elsewhere (Stahl et al., 2010; 2012). They found positive trends (wetter) in the winter months in most catchments. A marked shift towards drying trends was observed in April, gradu-

FIGURE 3.35

Drought frequency trends between 1951 and 2015, expressed as the number of events per decade: left to right, winter, summer, annual. In dotted areas trends are significant at the 95 % level
Source: adapted from Spinoni et al. (2017)

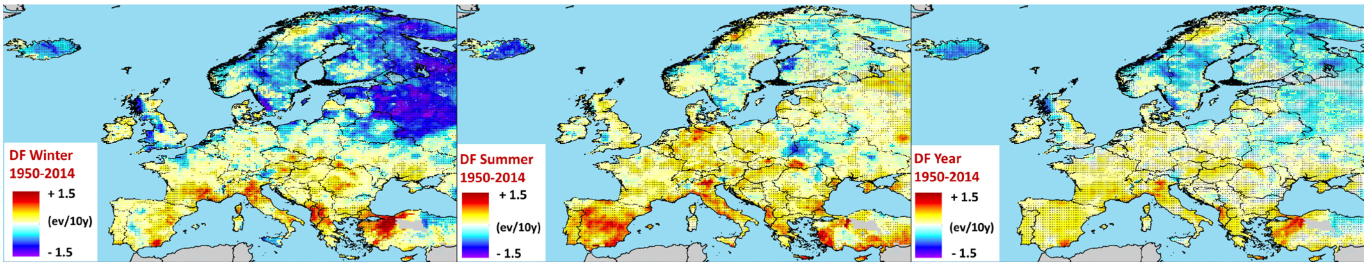
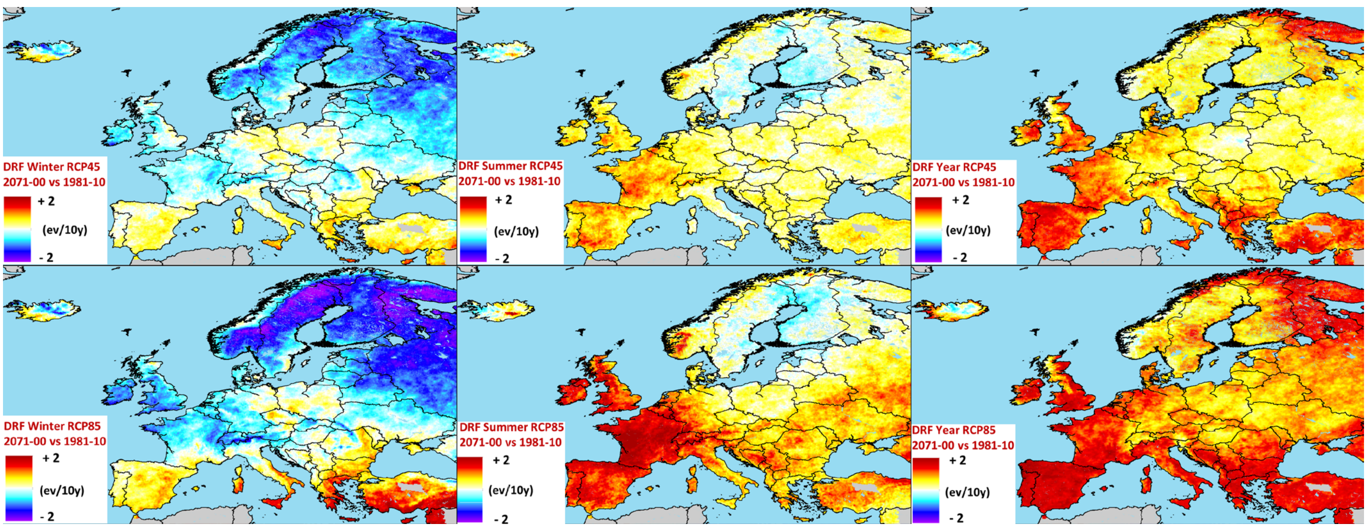


FIGURE 3.36

Drought frequency differences between the far future (2071-2100) and the recent past (1981-2010), expressed as the number of events per decade: left to right, winter, summer, annual; upper row scenario RCP4.5, bottom row RCP8.5
Source: adapted from Spinoni et al. (2017)



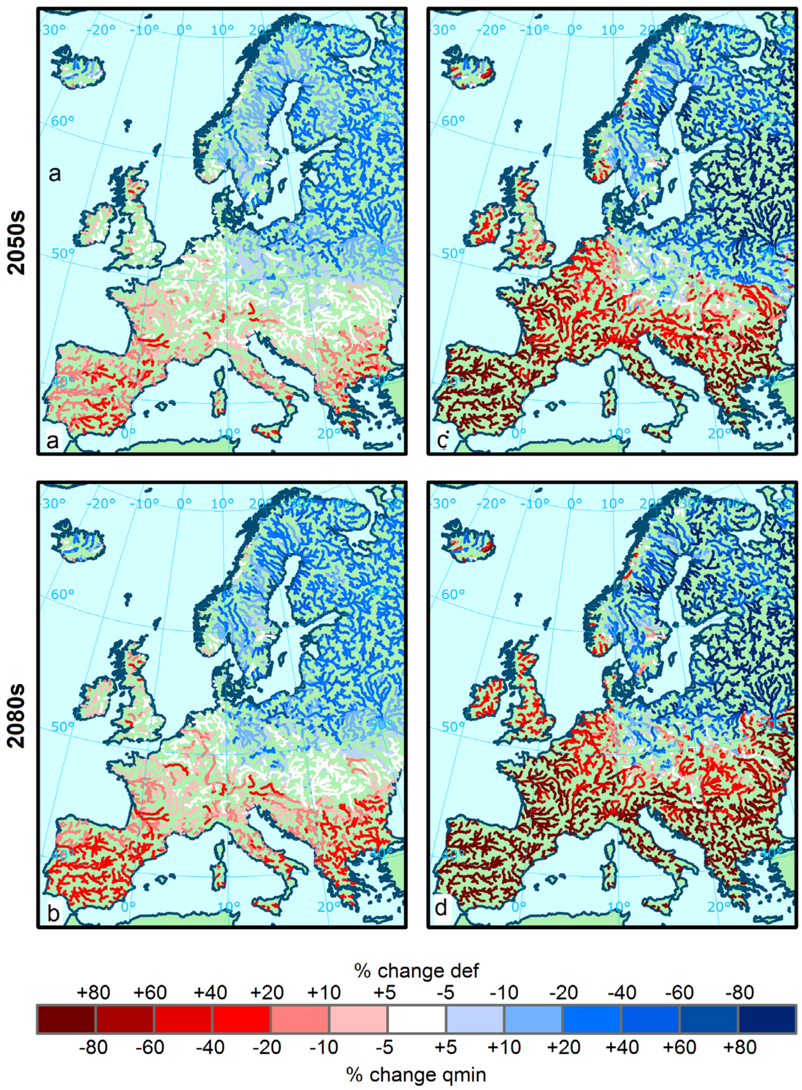
ally spreading across Europe to reach a maximum extent in August. Low flows have decreased in most regions where the lowest mean monthly flow occurs in summer, but vary for catchments that have flow minima in winter. Hannaford et al. (2013) show that trends are sensitive to the selected period (sign may change) owing to decadal climate variability.

Global changes in climate and socioeconomic patterns are expected to affect the development in space and time of river low flows (IPCC, 2012). Many river basins in Europe are likely to be more affected by severe water stress. Projected changes presented in different studies depend on the chosen drought indices (e.g. minimum flow, streamflow deficit), climate scenarios, temporal and spatial resolution of the climate signal and the hydrological representation. However, some coherent patterns emerge. Research studies based on multimodel ensemble climate and hydrological projections show consistent drought intensification both in terms of magnitude and frequency in south-western Europe. The main drivers are reduced precipitation and increased potential evapotranspiration. River low flows in these regions are expected to increase in severity by up to 40 % (Feyen and Dankers, 2009; Forzieri et al., 2014; Roudier et al., 2015) and current 100-year events could occur every 2 to 10 years (Lehner et al., 2006). The 20-year event of the river deficit volume is expected to increase by over 50 % both in the Mediterranean and European mid-latitudes by the end of the century (Figure 3.37). In contrast, northern regions of Europe will probably experience less severe hydrological droughts as a result of expected increased precipitation, which will outweigh the effects of higher evapotranspiration. In north-eastern Scandinavia and northern Russia, deficit volumes are expected to become more than 50 % lower. The projected changes are less clear in a transition zone (Forzieri et al., 2014; Roudier et al., 2015) because of the high climate uncertainty in changes in precipitation patterns.

The spatial drought patterns in Europe are confirmed by global studies

FIGURE 3.37

Future projections of river flow in Europe. Percent change in 20 year events of minimum flow (qmin, left) and deficit volumes (def, right) in the 2050s and 2080s relative to the control period (1961-1990)
Source: adapted from Forzieri et al. (2014)



on future hydrological drought by Prudhomme et al. (2014) and Wanders and Van Lanen (2015). The Caribbean and South and Central America are other hotspots where river flow is projected to be substantially affected, which is in line with the projected soil moisture decrease (Orlowsky and Seneviratne, 2013).

Future water consumption for domestic use, tourism, energy, manufacturing, agriculture and livestock sectors (Kämäri et al., 2011) will aggravate streamflow drought conditions by 10-30 % in southern, western and central Europe. Some regions (e.g. Eastern Europe) that are subject to little or small positive impacts of climate change could manifest a reversion of this trend by intensive water use, showing more severe drought situations (Forzieri et al., 2014). Wanders et al. (2015) illustrate in a global analysis that future drought impacts are very much dependent on the extent to which society will adapt to the gradually changing hydrological regime.

Droughts are likely to experience a much faster increase in severity and frequency of extreme events than other climate-related hazards, such as river floods, windstorms, wildfires and cold waves (Forzieri et al., 2016); thus, future impacts are expected to represent a major threat for society and the environment.

3.9.4 Drought impact

3.9.4.1 Drought impacts on society and environment

Drought impacts affect almost all parts of the environment and society. Unlike other natural hazards such as floods, earthquakes or hurricanes that result in immediately visible, mostly structural, damage, droughts develop slowly. Frequently, drought conditions remain unnoticed until water shortages become severe and adverse impacts on environment and society become evident. Drought impacts may be influenced by adaptive buffers (e.g. water storage, purchase of livestock feed) or can continue long after precipitation has returned to 'normal' (e.g. owing to groundwater or reservoir deficits). The slowly developing nature and long duration of drought, together with a large variety of impacts beyond commonly noticed agricultural losses, typically makes the task of quantifying drought impacts difficult (Wilhite, 2005b).

Quantification is, however, an important task, because, of all weather extremes, droughts have one of the largest impacts on society. Economic damage from drought events can be catastrophic, with a single drought event capable of causing billions of euros of damage (EC, 2007; EEA, 2011).

The impacts of droughts can be classified as direct or indirect (Tallaksen and Van Lanen, 2004; Meyer et al., 2013, Spinoni et al., 2016b). Examples of direct impacts are limited public water supplies, crop loss, damage to buildings due to terrain subsidence and reduced energy production. Indirect impacts relate to the secondary consequences on natural and economic resources. They may affect ecosystems and biodiversity, human health, commercial shipping and forestry. In extreme cases, drought may result in temporary or permanent unemployment or even business interruption and lead to malnutrition and disease in more vulnerable countries (Hiller and Dempsey, 2012). Figure 3.38 schematically illustrates possible direct and indirect social, economic and environmental impacts. Because of their very nature (i.e. the dependence of livelihoods and economic sectors on water), most drought impacts are indirect. These indirect effects can propagate quickly through the economic system, affecting regions far from the origin of the drought (Wilhite, 2002).

Drought impacts society and the environment (e.g. public water supply, agriculture, energy production, infrastructure, shipping, forestry, ecosystems and human health). Impact quantification is a prerequisite for drought management and policymaking.

Since droughts affect socioeconomic systems directly or indirectly, their damage may be tangible (market related) or intangible (non-market related). The latter are particularly difficult to quantify as they include, for example, ecosystem degradation or the costs of mitigation and long-term adaptation measures. Impacts of droughts usually cascade. For instance, a lack of water causing crop losses will subsequently prevent farmers from investing in new machinery, resulting in losses to the farm equipment dealer and producers in the business chain. As a consequence, governments may have to provide aid to the different sectors. As droughts often affect large areas, sometimes over several years, these cascading impacts can affect large parts of society. If drought is severe and widespread, impacts may spread further in the community, as well as to other sectors and regions.

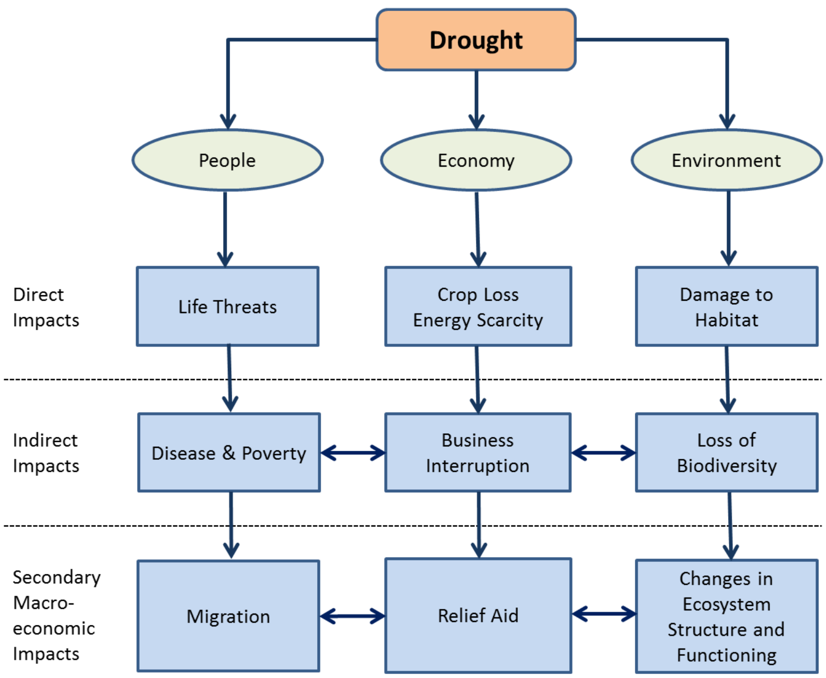
To foster risk management and adaptation strategies, drought impacts and the resulting damage and economic losses must be functionally linked with the monitored drought severity. Gudmundsson et al. (2014), Bachmair et al. (2015), Blauhut et al. (2015 and 2016), Naumann et al. (2015) and Stagge et al. (2015a), among others, have tested modelling approaches that link drought indicators such as SPI, SPEI, soil moisture, streamflow, groundwater and vegetation-related indicators to reported impacts. All studies conclude that a more quantitative monitoring of impacts and more research towards the quantification of the complex damage caused by drought is needed to improve such estimates. A survey by Bachmair et al. (2016) shows that many providers of Early Warning Systems (EWS) do monitor impacts, but this is not yet done systematically or quantitatively. The variable strength of the relationship between drought severity and recorded damage can often be explained by the sector-specific drought vulnerability and the adaptive capacity of the region affected.

The overall expected damage, estimated by HELIX (2016) and based on the combination of the observed impacts and estimated changes in the recurrence time of severe droughts, are projected to increase in the near future. In some regions such as southern Europe, Southeast Asia, eastern North America and south-east South America, damage could increase from twofold in the near future to tenfold in the far future compared with today (Figure 3.39).

These scenarios suggest that drought risk may increase for many economic sectors and vulnerable regions unless appropriate mitigation and adaptation measures are implemented. Since many regions with high population densities and, often, vulnerable societies relying on local agricultural production show large expected losses in Figure 3.39, they remain a high priority to target better impact monitoring and quantification as a basis for drought management and adaptation.

FIGURE 3.38

Schematic presentation of examples of drought impacts and their interrelations
Source: adapted from Jenkins (2011)



3.9.4.2 Health impacts

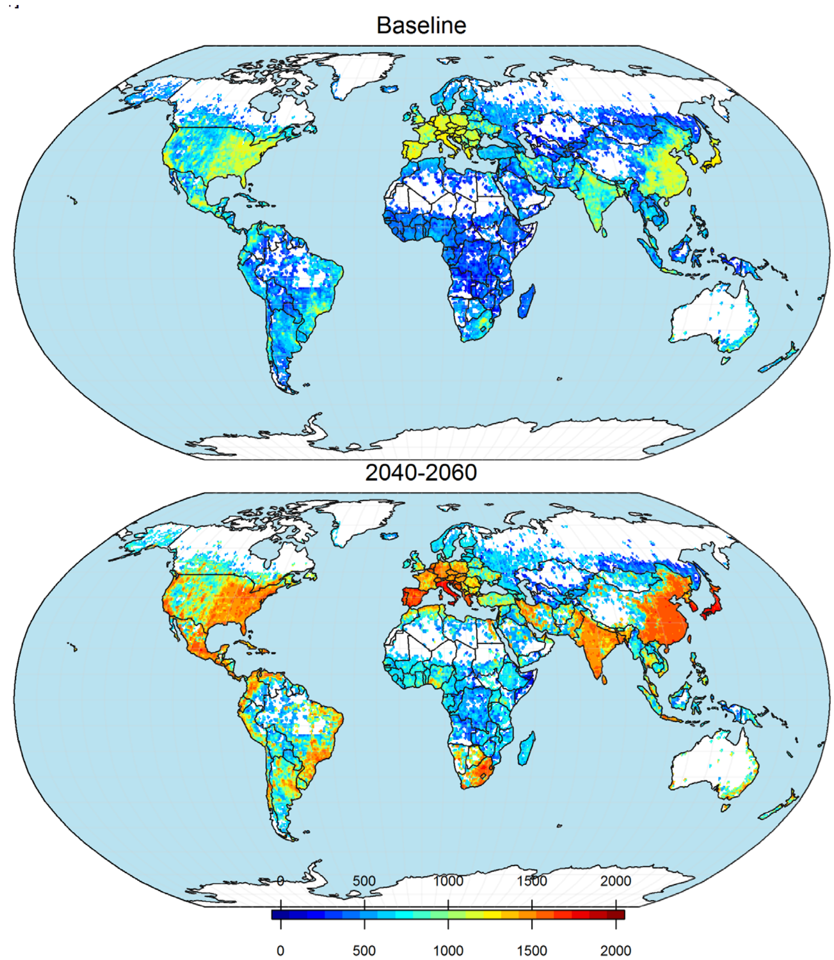
Between 1900 and 2015 drought affected 2.3 billion people worldwide and led to an estimated 11.7 million deaths (EM-DAT, 2009). Drought-associated impacts on people are often linked to health (WHO, n.d.). Health effects can be direct (increased morbidity and mortality) or indirect (economic disruption, infrastructure damage, forced migration). Health impacts include (1) malnutrition, (2) water-, vector- and air-borne diseases, and (3) mental aspects (WHO, 2012). Population vulnerability may be enhanced by socioeconomic factors, such as poverty, that force people to live on lands with poor soil fertility or in ecosystems at risk of drought.

Malnutrition

The World Health Organization (WHO) ranked malnutrition as the largest global health problem associated with climate change and drought (Campbell-Lendrum et al., 2003; IPCC, 2012). Exposure to drought has been associated with morbidity and mortality owing to the deterioration of people's nutritional state (Stanke et al., 2013; Friel et al., 2014; Sena et al., 2014). Water shortages may result in reduced food production (crop failure and livestock loss), leading to malnutrition and health risks, such as low birth weight (WHO, 2012). Vulnerable groups, such as pregnant women, children aged < 5 years and people living in shelters are mostly affected (Black et al., 2008; Gitau et al., 2005; Singh et al., 2006a, b; WHO, 1985).

FIGURE 3.39

Expected annual losses due to drought [in thousand USD] for the present (baseline) and the period 2040-60 according to seven different climate models and RCP8.5 (high-end scenario).
Country losses are disaggregated according to gridded GDP values. Source: HELIX project (Naumann et al., 2017)



Water-borne diseases

Shortage of water, lack of clean water and inadequate sanitation are typical during a drought. A number of water-borne infectious diseases have been linked to drought (Effler et al., 2001; Brandley et al., 1996). A direct link between drought and the transmission of the pathogens is, however, difficult to observe owing to other concurrent environmental factors and human vulnerability. Drought-induced stress in livestock and livestock use of human water resources may lead to high concentrations of pathogens and increase the risk of human exposure and infection, particularly after heavy rain following a drought. Poor hygiene and poor water quality for human consumption may result in the transmission of diarrheal diseases (WHO, 1985; Sena et al., 2014; Burr et al., 1978; Smoyer-Tomic et al., 2004).

Vector-borne diseases

Pathogens and vectors are sensitive to climatic and other environmental conditions, which is reflected in the characteristic geographic distribution and seasonal variation of vector-borne infectious diseases (Kilpatrick et al., 2012). While increased precipitation may increase mosquito densities owing to new aquatic habitats, mosquito densities may also increase dramatically following a drought (habitat rewetting) because of the reduced number of competitors and aquatic predators (Chase et al., 2003). Drought may boost the density of birds and mosquitoes around any water sources remaining and thus may accelerate the transmission of pathogens such as West Nile virus (WNV) within these populations, thereby increasing the risk of WNV outbreaks in humans (Shaman et al., 2005; Wang et al., 2010). Mosquitoes, which can efficiently transmit pathogens such as the dengue and chikungunya viruses, may adapt to drought in urban environments and exploit artificial aquatic habitats (e.g. water containers), thus elevating the risk of infection in humans (Brown et al., 2014).

Airborne diseases

Drought-related processes can result in atmospheric dust loadings and associated dispersion of microorganisms at various scales, which may have significant implications for human health. The WHO (2015) has identified drought and dust wind activity in sub-Saharan Africa as a risk factor for regional outbreaks of meningococcal meningitis. Dust storms and winds facilitate the transport of microorganisms favouring meningitis seasonality, which can have serious consequences for public health (Griffin, 2007, WHO, 2015; Agier et al., 2012). The mechanisms by which dust and climate may influence meningitis occurrence, along with outbreak location and severity are, however, not fully clear.

An association between respiratory and cardiovascular diseases could be shown in several regions, but little attention has been paid to West Africa, where desert winds and storms may cause more diseases, such as meningococcal meningitis (De Longueville et al., 2013, Garcia-Pando et al., 2014).

Mental health

Studies on the association between drought and mental health point to fears and anxieties among the rural population in particular, although suicidal thoughts have been recorded as more critical symptoms. (Polain et al., 2011; Carnie et al., 2011; Hanigan et al., 2012).

In summary, disease incidence is often more pronounced in drought-prone regions and affects more vulnerable population groups, such as children and the elderly, or people with difficult living conditions, which may be caused by poverty, for example. Enhancing drought resilience in regions with high population vulnerability and low adaptation capacity should, therefore, be reflected in relief aid programmes.

3.9.5 Analysing drought risk

Risk analysis is a major technique for measuring global progress in the implementation of the Sendai Framework for Disaster Risk Reduction (Aitsi-Selmi et al., 2015). Analysing risk is crucial to identify relief, coping and management responses that will reduce drought damage to society. The objective of risk analysis is to determine the underlying causes of drought damages resulting from the combination of drought hazard, drought exposure and drought vulnerability (Table 3.6).

3.9.5.1 Analysing hazard, exposure and vulnerability

Measuring drought hazard includes estimating the location, duration, intensity and frequency of water deficits over land. Traditionally, drought hazard has been characterised by meteorological indicators, but a simple precipitation shortage often does not translate into immediate concerns and impacts on the ground. Indeed, owing to the multiple-timescale nature of drought, its impacts can continue long after precipitation conditions have returned to 'normal' (see Chapter 3.9.4). Therefore, recent scientific developments have focused on combining meteorological indicators with indicators that take into account hydrological processes (e.g. soil moisture, groundwater and river flow), which reflect more closely the impacts felt on the ground.

Interactions between drought hazard, exposure and vulnerability underlie any comprehensive drought risk analysis, which is crucial for drought management and reducing drought impacts.

A review of existing drought hazard indicators by Bachmair et al. (2016) reveals the unsolved challenges of (1) designing and implementing indicators able to represent drought propagation across the whole hydrological cycle at different spatial and temporal scales, and (2) the systematic collection of impact data to enable validation and a better understanding of the variety of drought impacts on the ground.

To assess the impacts of drought hazard, the first step is to inventory and analyse the environment that can be damaged (Di Mauro, 2014). In the disaster risk-reduction community, exposure refers to the different types of physical entities that are on the ground and that can be adversely affected by a hazardous event, including built-up assets, infrastructures, agricultural land and the location and density of people (UNODRR, 2015). Since drought develops slowly and results in a great variety of impacts in most parts of the world, even in wet and humid regions, drought exposure is often measured for distinct water use sectors as a function of the location, timing, duration and amount of a water deficit (Dracup and Lee, 1980; Wilhite and Glantz, 1985). Proxy indicators of drought exposure include, for example, the distribution of crop and livestock farming, industrial and household water withdrawals, and the human population.

Since the location, severity and frequency of droughts are difficult to forecast (see Chapter 3.9.6.2), and since exposure expands as a result of economic and population growth, interventions to reduce drought impacts need to focus on mitigating the vulnerability of human and natural systems. This requires an understanding of who is vulnerable, to which impacts and the reasons for this vulnerability (Gbetibouo and Ringler, 2009). While tools such as drought management plans are key to deliver a structured and coordinated response when drought hits, drought vulnerability assessments (DVAs) can be used to support the design of mid- and long-term drought preparedness actions to increase structural resilience. As such, they provide a crucial link between drought management and water resources planning, where those actions have to be designed and agreed upon in an integrated way. A broad variety of factors have been used to determine vulnerability to drought (Table 3.7).

Some factors are specific to drought (e.g. the existence of drought management plans or the level of diversification of water sources), while others (e.g. poverty or the quality of social networks) are likely to influence vulnerability to an array of hazards in diverse sociopolitical and geographical contexts (Brooks et al., 2005; Cardona et al., 2012). A recent review of 46 assessments of drought vulnerability (González-Tánago et al., 2016) highlighted that data availability still represents a major constraint in building sound and policy-relevant vulnerability assessments. In particular, it is key to invest in the systematic, high-resolution collection of data on drought impacts, water uses,

TABLE 3.6

Components of drought risk analysis.

	Characterisation	Relevant data	Examples of studies
Hazard	Magnitude of a hydrometeorological deficit	Meteorological, hydrological and/or biophysical indicators	Sepulcre-Canto et al. (2012); Vicente-Serrano et al. (2010); Svoboda et al. (2002); Kogan (1995); McKee et al.(1993); Palmer (1965).
Exposure	Amount of elements subject to drought hazard	Amount and location of human populations, activities and/or ecosystems	Winsemius et al. (2015); Christenson et al. (2014).
Vulnerability	Susceptibility of exposed elements to damaging effects of drought hazard	Composite indicators that include environmental, social, economic and/or infrastructural components	González-Ténago et al. (2016); Naumann et al. (2014); Brooks et al. (2005); Cutter et al. (2003).
Overall risk	Likelihood of impact	Measured in a probabilistic scale linked to intervention policies	Blauhut et al. (2016); Carrão et al. (2016); Kim et al. (2015); Eriyagama et al. (2009); Peduzzi et al. (2009).

non-conventional water sources and the quantitative and qualitative status of water resources. Moreover, the review revealed the need for greater transparency in the design of drought vulnerability assessments and for increased efforts in the validation of the results.

3.9.5.2 Estimating drought risk

Definitions of risk are commonly probabilistic in nature, referring to the potential impacts or the likelihood of harmful consequences (i.e. environmental, economic, social and/or infrastructural) from a particular hazard to an exposed element in a future time period (Blaikie et al., 1994; Cardona et al., 2012; Carrão et al., 2016). Therefore, the estimation of drought risk requires the development of a model that combines drought hazard with relevant indices or metrics of drought exposure and vulnerability (Government Office for Science, 2012).

An entry point for both understanding and addressing drought risk is to use quantitative measures of historical impacts as proxies for its estimation (Brooks et al., 2005). In particular, historical data relating to socioeconomic losses might be used as a retrospective measurement of drought risk to forecast the impacts arising from the interaction of hazard, exposure and vulnerability. For example, Peduzzi et al. (2009) carried out a global assessment of drought risk by fitting the number of human casualties to the determinants of drought risk by means of a generalised linear regression. More recently, Blauhut et al. (2015; 2016) tested the capability of logistic regression to predict the likelihood of drought impacts (LDI) in Europe for different sectors of activity from a set of drought risk determinants. Regression analyses are generally desirable from a risk assessment viewpoint because they may be validated from observed historical data. However, relying on historical impacts has some limitations when estimating current and future drought risk (Government Office for Science, 2012). Foremost, the number of affected people and the types of impacts vary by region, thus hampering consistent broad-scale analyses. For example, drought in developing countries can contribute to malnutrition, famine and loss of human lives, whereas in developed countries it primarily results in economic losses. Second, these analyses do not account for shifts through time in the distribution of exposure or vulnerability

TABLE 3.7

Examples of factors included in selected drought vulnerability assessments
Source: modified from González-Tánago et al. (2016)

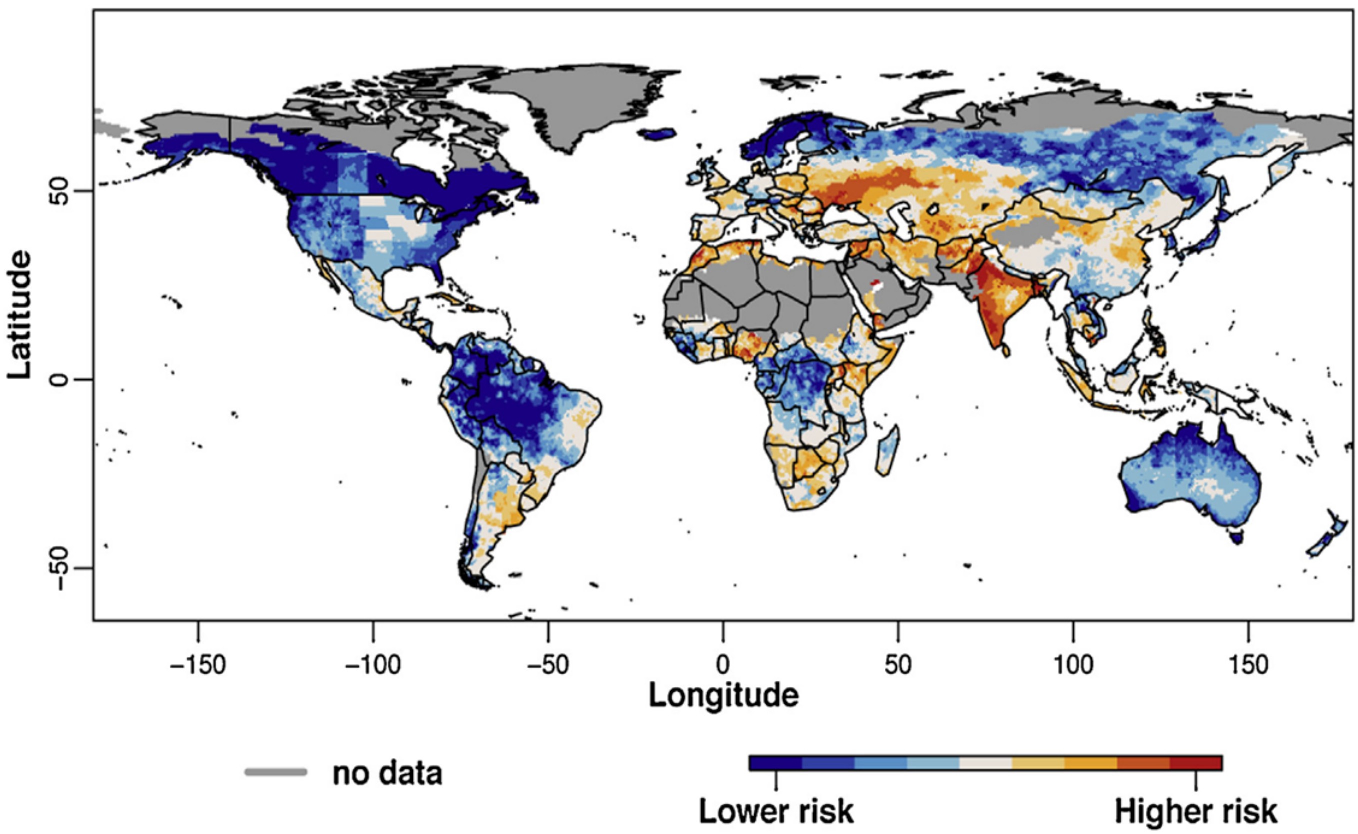
	Sub-dimension	DVAs		Most frequent factors (#of DVAs)
		#	%	
Biophysical dimension	Drought characteristics	17	41%	SPI (3), NDVI (4)
	Climatic components: rainfail, evapotranspiration, temperature	20	49%	Average annual precipitation (9)
	Soil characteristics and topographic factors	20	49%	Soil water-holding capacity (10)
	Water resources: runoff storage capacity. Surface and groundwater	19	46%	Status groundwater (12) and surface water (10)
	Water uses	11	27%	Agricultural water use (9)
	Land use	17	41%	Agricultural land uses (9)
Socioeconomic dimension	Socio-cultural (demography, education, health, gender, drought awarness, etc.)	29	71%	Population (24) and education (16)
	Economic and financial resources	28	68%	Economic resources (20), agricultural income (17), employment (9)
	Institutional, Policy and Governance (social networks, taxes, governmental programs, participation, etc.)	14	34%	Government presence or programs (9)
	Technical, technological and infrastructural (irrigation, tillage, improved seeds, fertilisers, access to services, etc.)	28	68%	Irrigation (23)
	Others ("Others")	4	10%	Impacts

to loss, thus biasing the predictions (Güneralp et al., 2015). Finally, impacts may be available only for short timescales and unavailable in some countries (Below et al., 2007), while the available records often do not include the most extreme cases to tune the regression models (Government Office for Science, 2012).

More recently, composite indicators have been proposed to estimate drought risk, for example by Naumann et al. (2014), Kim et al. (2015) and Carrão et al. (2016). Composite indicators are mathematical combinations of risk determinants that have no common unit of measurement (OECD/JRC, 2008). For example, Carrão et al. (2016) used a multivariate and non-parametric linear programming algorithm, a Data Envelopment Analysis (DEA), to aggregate proxy indicators of hazard, exposure and vulnerability into a composite statistic of global drought risk (Figure 3.40). Its values are not an absolute measure of economic losses or damage to human health or the environment, but a relative statistic that provides a regional ranking of potential impacts with which to prioritise actions to reinforce adaptation plans and mitigation activities. Figure 3.40 illustrates that drought risk is generally higher for populated areas and regions extensively exploited for agriculture, such as South-Central Asia, southeast South America, Central Europe and the Midwestern United States. This indicator, while useful for risk assessments in the agricultural sector, may not be adequate for analysinf the risk in other sectors, such as energy production (hydropower, cooling of

FIGURE 3.40

Global map of drought risk.
Source: Carrão et al. (2016)



nuclear plants), navigation and transportation (waterways), or recreation, which should be part of any comprehensive drought risk management plan.

Composite indicators and impact models represent alternative but complementary ways of approaching drought risk estimation at different scales and coordination levels. Since drought impacts are context specific and vary geographically, regression models are most important for local to national management when preparedness plans and mitigation activities are put in practice, while composite indicators can identify generic leverage points in reducing impacts from drought at the regional to global scales.

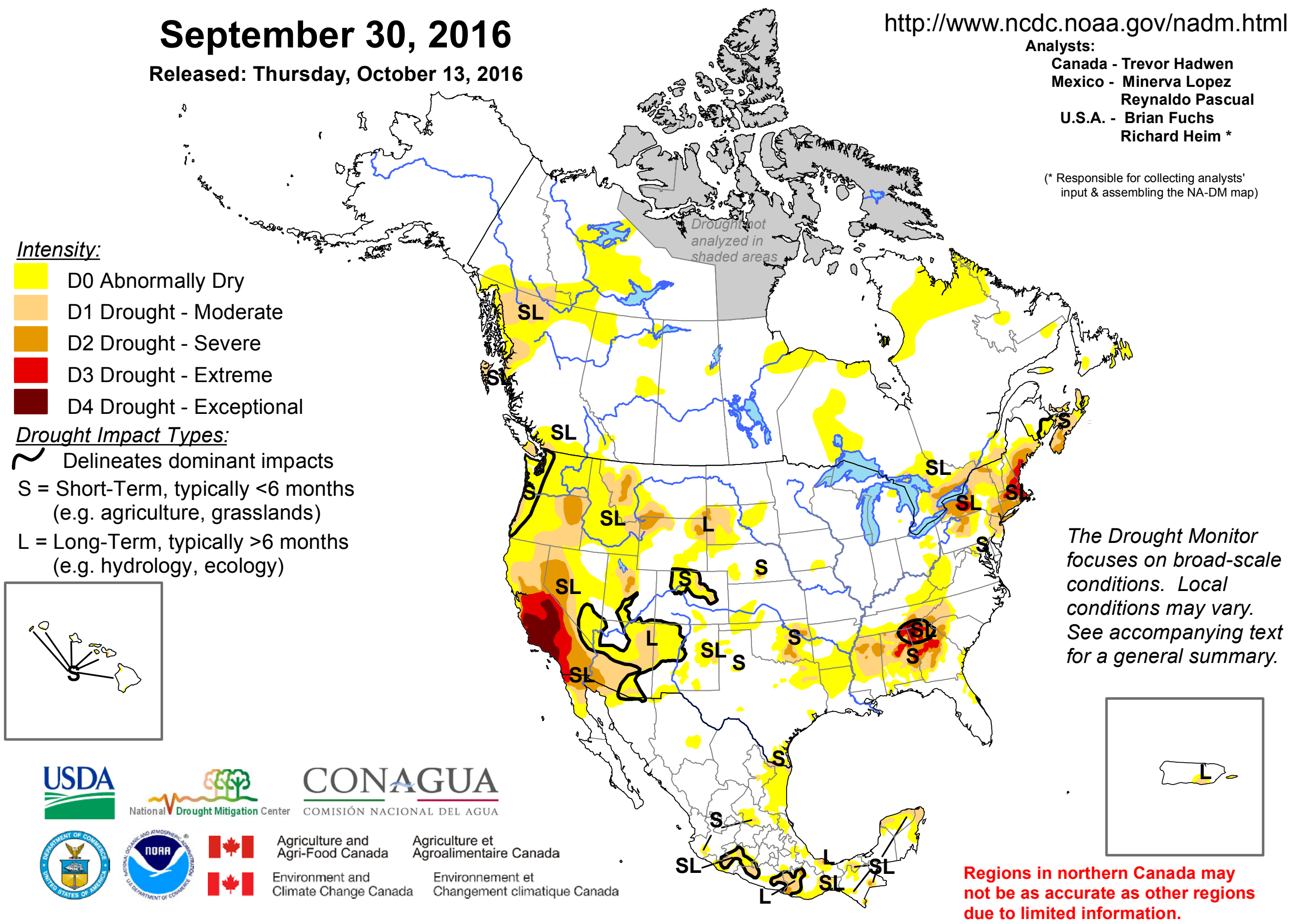
3.9.6 Managing drought risk

3.9.6.1 Drought monitoring

Drought monitoring and forecasting systems are an essential component of integrated drought management. They provide the necessary and timely information for stakeholders to analyse drought hazards for use within their decision-making processes (WMO, 2006; Bailey, 2013; Wood et al., 2015). In recent decades, such systems have been developed at different

FIGURE 3.41

The North American Drought Monitor
Source: NOAA (2017)



scales from the local or community scale up to the global level, illustrating the broad variety and complexity of users addressed by these systems. Since droughts affect extended regions that frequently cross national borders, it is important to maintain harmonised systems at different scales that provide comparable information and allow for an integrated monitoring of the evolving events. This is even more important with aquifers and river basins that are frequently transboundary and with globally interconnected economies, resulting in primary and secondary impacts that are felt across many countries and even globally.

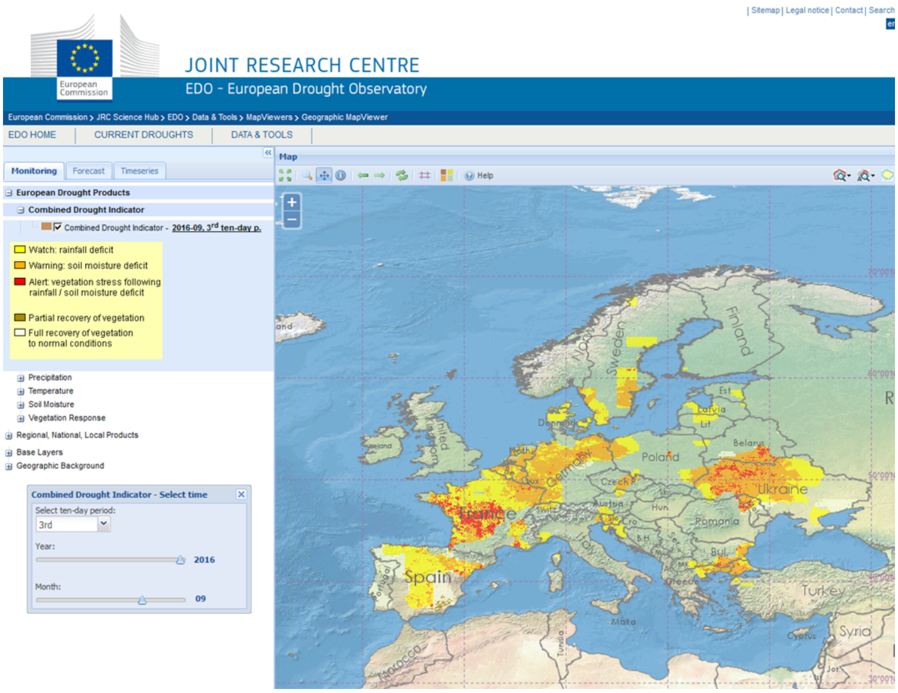
Available information typically includes meteorological, hydrological and remote sensing-based indicators, allowing for an assessment of the extent and severity of drought events across continents. More specific indicators for water management often become available at the regional to local levels. While the first type of information is targeted at policy and high-end decision-makers in the water management sector and at the general public (i.e. awareness raising indicators), the latter is targeted at water managers and stakeholders at the river basin or sub-basin level (i.e. management indicators).

A well-known example of continental systems is the North American Drought Monitor (NADM), which provides monthly information based on a suite of hydro-meteorological indicators, integrated with expert knowledge into a drought map showing five drought intensity levels, ranging from abnormally dry to exceptional drought. A suite of forecasting products and a seasonal outlook complement the picture. It is based on the concept of the weekly updated US Drought Monitor (USDM, Svoboda et al., 2002) and the US National Drought Information System (NIDIS, Pulwarty and Verdin, 2013), combined with information and expert knowledge from Canada and Mexico (Figure 3.41). Information is provided in the form of maps and analyst reports.

Harmonised monitoring and forecasting of a suite of drought indices is crucial in drought management and information interchange across borders. It contributes to a move from reactive to pro-active risk management.

FIGURE 3.42

The European Drought Observatory (EDO). Example of the Combined Drought Indicator (CDI) for the period 21 to 30 September 2016. Source: EDO (2017)



In Europe, the European Drought Observatory (EDO) provides maps of 10-day and monthly updates on the hydro-meteorological situation and the occurrence and evolution of drought events, including a 7-day forecast of soil moisture. In addition, a Combined Drought Indicator for agriculture and ecosystem drought analyses the drought propagation from a rainfall deficit through reduced soil moisture to impacts on the photosynthetic activity of the vegetation (Figure 3.42). The goal of such combined indicators is to provide easy to understand sector-specific information for decision-makers in the form of alert levels (Sepulcre-Canto et al., 2012). Like the NADM, the EDO delivers analyst reports during exceptional events, albeit not in a regular manner. The EDO is implemented in a nested manner, allowing for information to be processed and stored at the appropriate levels (i.e. the river basin, country or continental level). To allow for comparability between levels, a set of core indicators are processed following agreed algorithms.

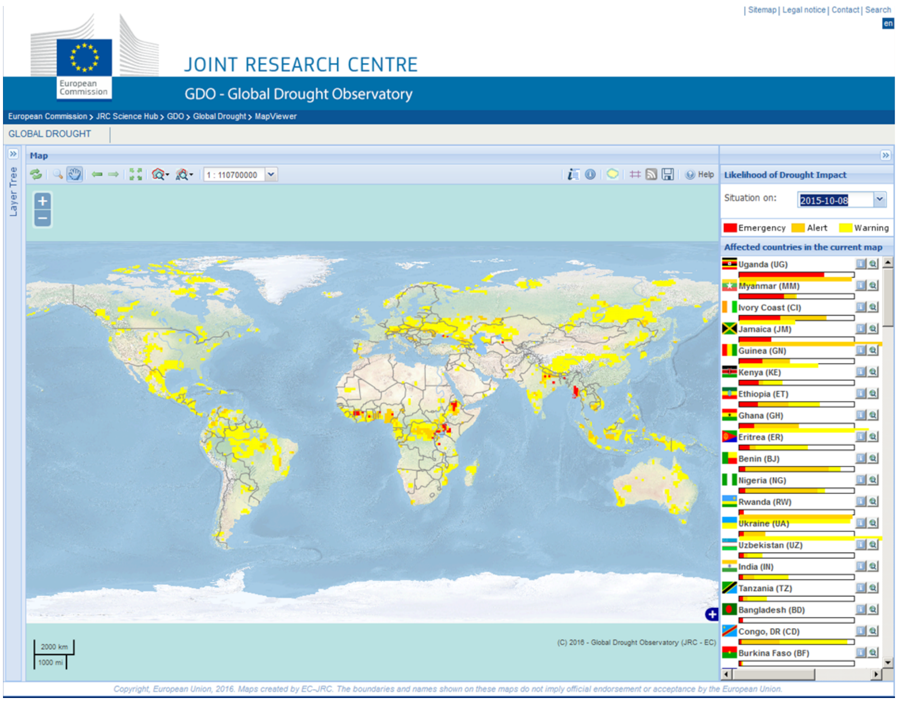
Challenges to drought monitoring and early warning are the continuous availability of indicators covering the various hydro-meteorological components and their combined analysis into usable information for the decision-making process at different levels. Important variables to monitor include precipitation, snow pack and snow water equivalent, temperature, evapotranspiration, river flow, reservoir storage, lake levels, groundwater levels, soil moisture and vegetation vigour, among others. The recently published Handbook of Drought Indicators and Indices (WMO and GWP, 2016) provides a good overview of frequently used indicators.

Cooperation between various entities ensures ownership at all levels, which is important to sustain EWSs. National Meteorological and Hydrological Services (NMHSs), as well as regional and subregional centres, are important partners in this task as they routinely monitor many of the required input variables. This, however, requires the exchange of data and interoperability between systems.

Two other major challenges exist with monitoring and forecasting systems. The first relates to linking drought severity with drought impacts in the variety of economic, social and environmental sectors. Consideration of this challenge is slowly being addressed with several studies in the United States and Europe (Chapter 3.9.5.1) and with systems such as the Global Drought Observatory (GDO), developed by the European Commission JRC for the European Union Emergency Response Coordination Centre (ERCC) and Humanitarian Aid services aim to include sector-specific vulnerabilities for assessing the Likelihood of Drought Impact (LDI). The GDO system shown in Figure 3.43 presents a map of the LDI together with a hierarchical list of all affected countries visible in the map. The second challenge relates to developing an understanding of how decision-makers will use the information being disseminated from monitoring and forecasting systems. That challenge needs to be investigated through social science-based research projects and interactions with key users of the information. An example for such interaction is implemented by the US NIDIS system (Pulwarty and Verdin, 2013).

FIGURE 3.43

The Global Drought Observatory (GDO). Example of Likelihood of Drought Impact (LDI) for the period 8 to 15 October 2015.
Source: GDO (2017)



3.9.6.2 Drought forecasting

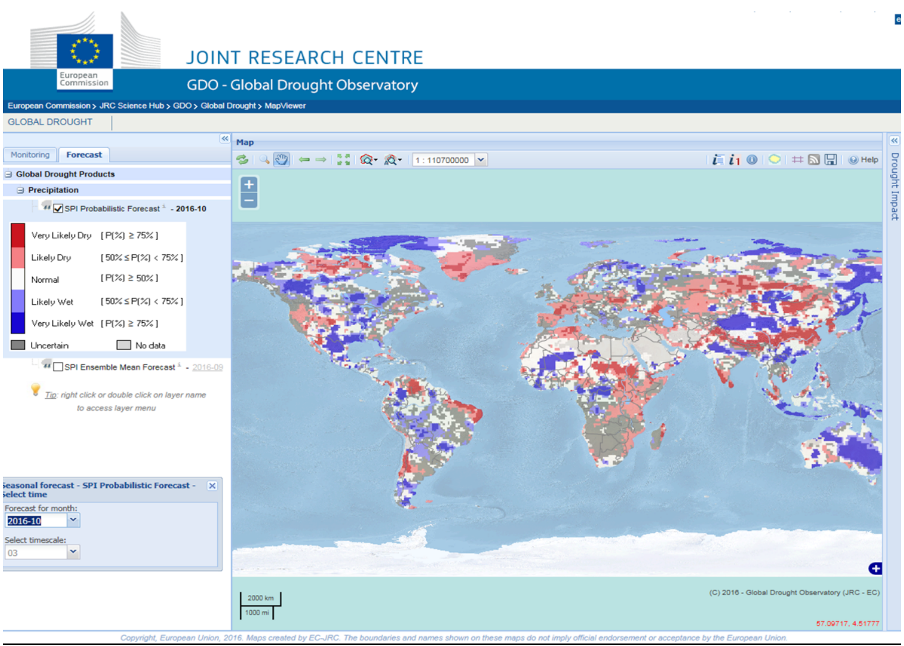
Forecasting the onset or likely evolution of an ongoing drought over the weeks and months ahead or over the season is important to trigger actions for mitigating negative impacts on human activities and environmental processes. Decision-makers and end users require adapted and robust forecast indicators that are capable of informing about the onset, possible duration, intensity and end of drought conditions (Chapter 3.9.6.1). The timescale of this forecast is considered a challenge as it stands between medium-range forecasting, which is strongly related to initial conditions, and the seasonal timescale, which is mainly driven by oceanic variability and large-scale climate features such as the El-Niño phenomenon (Vitart, 2014).

The lead time and duration of drought forecasts should be adapted to the needs of the region. In Europe, where resilience is higher owing to the widespread availability of irrigation systems, needs are more related to the forecast of long-term droughts, although shorter lead times are relevant for water-borne transport. In Africa, where agriculture is mainly rainfed, a short-term deficit of precipitation constitutes a higher risk. In these regions, the forecasts of dry spells (short-term droughts of about 10 days) is also important (Winsemius et al., 2014; 2015).

Studies have demonstrated that droughts can be forecasted using stochastic or neural networks (Kim and Valdes, 2003; Mishra et al., 2007) with a reasonably good agreement and with 1- to 2-month lead times. Linking weather types to drought (Fleig et al., 2011; Kingston et al., 2013) and statistical downscaling methods using weather types can also be used (Lavaysse et al., 2017). Eshel et al. (2000), for example, used the North Atlantic sea level pressure precursors to forecast drought over the eastern Mediterranean. Forecasts of droughts can also be produced using deterministic Numerical Weather Prediction Models. Such forecasts are highly uncertain as a result of the chaotic nature of the atmosphere, which is particularly strong on a subseasonal timescale (Vitart, 2014). In general, the published literature indicates that the skill of the precipitation fields produced by Numerical Weather Predictions over Europe is low (Richardson et al., 2013; Weisheimer and Palmer, 2014). Predictions will be better in regions where precipitation origins are related to large-scale structures, such as synoptic perturbations or oceanic anomalies (e.g. mid-latitudes), while regions with strong local drivers (e.g. West Africa) will record lower scores. However, these analyses tend to be performed from the point of view of weather forecasting and do not incorporate specific properties that are relevant for drought forecasting, such as persistence. Therefore, ensemble prediction systems have been developed that forecast multiple scenarios of future weather. These forecasts become particularly important to assess the risks associated with high-impact and rare weather events such as tropical cyclones or droughts (Hamill et al., 2012; Dutra et al., 2013, 2014). The European Centre for Medium-range Weather Forecast (ECMWF) provides two different types of ensemble forecasts for this time range: an extended range forecast, with lead times of up to 45 days, which is issued twice a week, and a seasonal forecast, with

FIGURE 3.44

GDO: Probabilistic Forecast for October 2016 based on SPI-3 from the ECMWF Ensemble system (experimental product, data courtesy ECMWF). Source: GDO (2017)

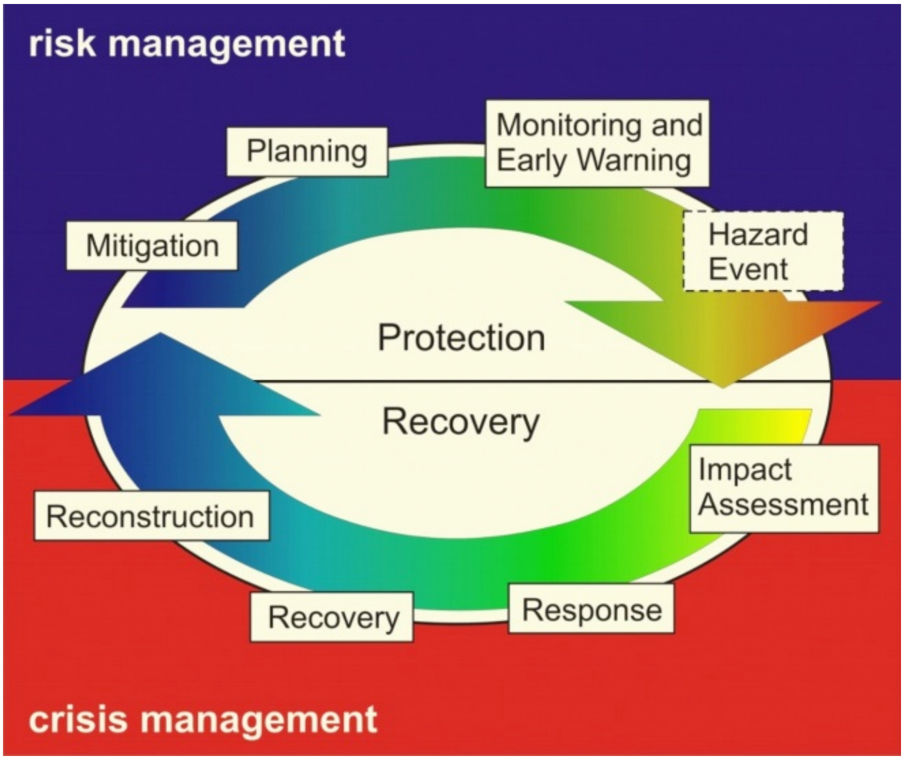


lead times of up to 13 months, issued once a month. The extended-range forecast incorporates more recent model developments and is usually of higher spatial resolution (Vitart, 2004). The seasonal forecasting system is based on an older model cycle (Molteni et al., 2011), among other significant differences. In the case of droughts, an analysis including both the numerical forecasting skill and the possibilities for binary decisions to issue drought warnings has shown that 40 % of droughts can be correctly forecasted 1 month in advance over Europe (Lavaysse et al., 2015). While the performance of these subseasonal forecasts is still behind the current medium-range weather forecasts, the ongoing efforts by academia and operational centres are encouraging. An example of monthly forecasting of the probability of drought occurrence based on the ECMWF ensemble system is shown in Figure 3.44.

Finally, the prediction skill depends on the indicator used. Other studies, for example, analysed the prediction of drought based on soil moisture, groundwater or a multivariate index (e.g. AghaKouchak, 2014; Hao et al., 2014; Mendicino et al., 2008). Depending on the region, results can be better than using meteorological indicators, mainly due to the larger persistency (lower variability) of the variables. However, the corresponding data availability and quality, as well as the skill scores, need to be carefully assessed.

FIGURE 3.45

The Cycle of Disaster Management illustrating the importance of risk management in reducing future drought-related impacts.
Source: National Drought Mitigation Center, University of Nebraska-Lincoln.



3.9.6.3 Drought management

Most officials at all scales traditionally deal with drought impacts in a reactive fashion when a drought event takes place. This reactive approach, called crisis management, has often been uncoordinated and untimely (GSA, 2007; Wilhite and Pulwarty, 2005). In addition, crisis management places little attention on trying to reduce drought impacts caused by future drought events.

Drought risk management, however, is a paradigm that focuses on trying to reduce future impacts by improving drought monitoring and early warning, planning and mitigation strategies (Wilhite et al., 2005a). It is an approach that is inherently proactive and directed at identifying who and what is at risk, why they are at risk and how individuals respond to events.

The concept of drought risk management is illustrated in Figure 3.45, which demonstrates the Cycle of Disaster Management. Although this cycle applies to all natural hazards, which is why some of the components of the cycle (such as reconstruction) apply better to other hazards, it is also applicable for droughts. The bottom half of the cycle represents crisis management, which will always be necessary in some form to respond to the drought impacts of a current event. However, Figure 3.45 highlights that the actions of monitoring and prediction, planning and mitigation need to take place in order to reduce future drought impacts. These actions are considered to be a part of a drought risk management approach. Drought monitoring and prediction involves the continuous assessment and anticipation of indicators of drought severity, spatial extent and related impacts. Using this information to elicit response is called 'early warning' (Hayes et al., 2012). Because decision-makers require accurate early warning information to implement effective drought policies and response and recovery programmes, drought monitoring and prediction are essential for drought risk management and illustrate an important connection between risk and crisis management (Wilhite and Buchanan-Smith, 2005).

The objective of drought planning, the second component of drought risk management, is to reduce the impacts of drought by identifying the principal activities, groups or regions most at risk and developing strategic actions and programmes that address these risks, as well as response actions that can be taken during a drought event. Drought plans provide an effective and systematic means of assessing drought conditions, developing mitigation strategies that reduce risk in advance of drought, and devising response options that minimise economic stress, environmental losses and social hardships during drought (Wilhite et al., 2005b). This overall emphasis on drought planning is fundamental to drought risk management at any decision-making level. Incorporating planning will help decision-makers to prepare for multiple hazards, including drought and climate change, and will promote sustainability and natural resources management, leading to greater economic and societal security at all levels (GSA, 2007).

The third component of drought risk management is the implementation of appropriate drought mitigation strategies, which are the specific activities taken before a drought occurs that reduce the long-term vulnerability to droughts. According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2006), there are currently a limited number of tested strategies available by which to identify appropriate drought risk-reduction strategies. Furthermore, they concluded that 'it is essential to identify and demonstrate effective approaches and opportunities for drought mitigation and preparedness, including case studies to show examples of good as well as weak policies. Policymakers, scientists, media, and the public often need to see actions-at-work in order to foster buy-in to similar efforts.'

As drought monitoring systems improve in many locations (see Chapter 3.9.6.1), and as policymakers begin to think about trying to implement drought risk management strategies, such as planning and mitigation, an important feedback loop has emerged whereby better drought management drives the need for improved drought monitoring and, in turn, improved drought monitoring encourages more effective drought management (Hayes et al., 2012). As drought plans become more specific in space and time, the need for information at higher spatial and temporal resolutions increases.

An example of this type of coevolution in drought monitoring and risk management has occurred over the past decade in the United States, whereby improvements in the US Drought Monitor (USDM) (Svoboda et al., 2002) product have led to shifts in national agricultural policies, inspiring additional advancements in the spatio-temporal resolution of drought monitoring to support implementation of these policies at a local scale.

Although progress in drought risk management has been slow, there has been some success around the world (Wilhite et al., 2005a). A great example of this at the global scale occurred with the High-level Meeting on National Drought Policy (HMNDP, March 2013), which was co-organised by the WMO, the Secretariat of the United Nations Convention to Combat Desertification (UNCCD) and the Food and Agriculture Organization of the United Nations (FAO), in collaboration with a number of UN agencies, international and regional organisations.

The Policy Document of the HMNDP (UNCDD, FAO and WMO, 2013) lays out the essential elements of a National Drought Policy, namely:

- Promoting Standard Approaches to Vulnerability and Impact Assessment;
- Implementing Effective Drought Monitoring, Early Warning and Information Systems;
- Enhancing Preparedness and Mitigation Actions; and
- Implementing Emergency Response and Relief measures that reinforce National Drought Management Policy Goals.

These elements are considered to be the key pillars of a National Drought Management Policy. These pillars have been used in many different initiatives including the Integrated Drought Management Programme (IDMP) and the Windhoek Declaration of the African Drought Conference (UNCCD, 2016). One of the successes of HMNDP is that it has drawn the attention of the international organisations and national governments to focus on proactive policies.

The strong call for a framework in the form of a policy that combines different approaches that have been considered key in moving from a crisis management approach to a risk management approach has led to the launch of the IDMP by the WMO and the GWP at the HMNDP in March 2013. The objective of the IDMP is to support stakeholders at all levels by providing policy and management guidance and by sharing scientific information, knowledge and best practice for an integrated approach to drought management.

The strength of the IDMP is to leverage activities of its various partners to determine the status and needs of countries and to move forward collectively to address these needs. The IDMP also uses the network of NMHSs and related institutions affiliated with the WMO, the United Nations specialised agency for weather, climate and water, and the Regional and Country Water Partnerships of the GWP as the multistakeholder platform to bring together actors from government, civil society, the private sector and academia working on water resources management, agriculture and energy.

Based on one of the tools that has been instrumental in the development of drought preparedness plans in the United States, the 'National Drought Management Policy Guidelines — A template for action' (WMO and GWP, 2014) were developed from existing material to focus on a national policy context and to draw on experiences from different countries. The purpose of these guidelines is to provide countries with a template that they can use and modify for their own purposes. Countries should not blindly use the 10-step process. The guidelines should be modified and adapted to local needs and experiences. For example, the Central and Eastern European countries have distinguished seven steps.

3.9.7 Conclusions and key messages

The key challenge in reducing drought risk is to move from the prevailing reactive approach, fighting the highly diverse drought impacts, to a pro-active society that is resilient and adapted to the risk of drought (i.e. through the adoption and implementation of pro-active risk management). This requires practitioners, policymakers and scientists to use a consistent set of drought definitions and characteristics. Observed and projected trends in drought hazard need to be understood and considered in the management plans. The hazard has to be connected to manifold impacts (e.g. on water supply, food security, energy production, transport, health, and ecosystems). Current, as well as future, societal exposure and context-specific vulnerability should be identified to eventually assess the evolving drought risk. Through knowledge of all these aspects, drought risk can be managed through a set of institutional, structural and operational measures, including monitoring and seasonal forecasting. There is, moreover, an ongoing need to consider the institutional aspects of 'capacity' and 'coordination' at national and local levels, particularly where the required sustained collaborative framework among research, monitoring and decision-making/management is lacking (Pulwarty and Sivakumar, 2014). Central to the above is the development, support and training of a cadre of professionals and policy entrepreneurs who view the role of linking drought science, policy and risk management practices as a core goal over the long term.

Recommendations have been set according to the three pillars of DRMKC. Links to the various mentioned activities and projects are provided at the end of the chapter (see Web Resources for Chapter 3.9 in References chapter 3 - section III).

Partnership

In Europe, several drought science partnerships exist: (1) the European Drought Centre (EDC), (2) the European Drought Observatory (EDO), and (3) the Drought Monitor for South Eastern Europe (DMCSEE). On the global level, the WMO/GWP Integrated Drought Management Programme (IDMP) fosters collaboration on drought management in the broad sense. The EDC shares expertise from scientists, water managers and stakeholders, and contains the European Drought Impact Report Inventory (EDII). The EDO and

DMCSEE monitor current drought conditions. The EDO also includes a forecast of drought conditions and up-to-date information on drought in the media. The EDO also performs analyses of past trends and of future projections under different scenarios for the 21st century. The IDMP coordinates regional initiatives around the globe (e.g. in Central and Eastern Europe, West Africa, Central America and South Asia), covering a wide range of drought aspects. Professional networks dealing with drought in Europe and beyond are, for example, the UNESCO EURO FRIEND-Water Low Flow and Drought network and the IAHS Panta Rhei Working Group on Drought in the Anthropocene. Further development of and collaboration between these partnerships is important to advance our understanding of drought and to improve our capacity to cope with this important threat to our societies.

Knowledge

Recent EU drought research projects (i.e. DROUGHT-R&SPI, DEWFORA, PESETA) and regional cooperation programmes such as EUROCLIMA, as well as several national initiatives (e.g. Jucar Basin, Spain, Box 3.2), have advanced the knowledge base with better access to information, guidelines and services on: (1) drought monitoring, prediction and early warning, (2) drought impacts and links with the hazard, (3) drought risk assessment, risk reduction and drought response, and (4) policy and planning for drought preparedness and mitigation across sectors. Chapters 3.9.2 to 3.9.6 illustrate progress made in these fields over the last decade. It is likely that the frequency, severity and scale of droughts will increase in multiple regions in Europe and elsewhere, affecting many economic sectors (e.g. agriculture, water-borne transport, energy), the environment (e.g. aquatic ecosystems, biodiversity) and human well-being (health). It is therefore important to improve societal preparedness for the related risks and to adapt to the future challenges resulting from droughts.

Innovation

The European Drought Impact Report Inventory - EDII (Stahl et al., 2016), has created a good base on which to learn more about the multifaceted impacts of drought, but needs to be continuously updated and expanded to cover the whole of Europe. Similar inventories need to be established for other parts of the world. This allows the establishment of improved links between impacts and drought hazard on the one hand, and a better assessment of drought risks and how to manage these across sectors on the other hand. Furthermore, context-specific drought vulnerability profiles for the river basins across Europe that also consider projections need to be elaborated. Scientific innovation is required on seamless drought prediction to address multi-monthly and seasonal forecasting, as well as drought projections for the intermediate and far future. Drought management should be put in a multihazard setting, which requires land and water management that integrates policies and measures for the different hazards (droughts, floods, wildfires and heat waves). A follow-up of the past EU working group on Water Scarcity and Drought is required to effectively disseminate progress on drought, including guidelines and good practices among EU Member States and beyond.

BOX 3.2

Jucar Basin Case Study

Proactive and participatory drought planning and management in a semi-arid water-scarce system

The Jucar Basin District (JBD) (42 989 km^2) is located near Valencia in eastern Spain. Most of the area can be classified as semi-arid, and precipitation is highly variable in space and time.

Multiyear droughts are common, as illustrated by the Standardized Inflow Index for the naturalised flow into the Tous Reservoir (lower JBD) (Figure 3.46). The most significant water use is attributable to (1) irrigated agriculture (400 000 ha, 80 % of water demand), (2) urban areas (4.3 million inhabitants) and (3) industry (including hydroelectricity production and nuclear plant cooling). The water exploitation index (water demand / natural renewable resources) is approximately 86 %. Water scarcity is acute, resulting in high environmental stress and water quality deterioration. Water allocation has caused political and social conflicts between users and areas. Droughts have exacerbated these problems and are projected to become even more frequent and severe as a result of climate change.

In the JBD, water has been intensively exploited over centuries and adaptation to drought has been a common feature. Institutional and legal developments (e.g. irrigation district associations and water tribunals) were fostered centuries ago and are still working. However, while many measures (e.g. building infrastructures) were taken to decrease vulnerability, drought response remained mainly reactive. In 1936, the participative JB Public-Private Partnership (JBPPP) was founded, and nowadays it includes many stakeholders (e.g. national, regional and local administrations, water users and environmental non-governmental organisations (NGOs)).

The JBPPP does the basin administration, enforces decisions and recovers costs of infrastructures building, operation and maintenance. It provides a very good framework for governance, as well as a good forum for conflict resolution, which is fundamental in drought management. Within the JBPPP, there has been an improvement in knowledge of water resources management since the 1980s through the use of models and collaborations with scientists. Initially the focus was on individual basin components, but in the 1990s an integrative decision support systems (DSS) at the basin scale was designed for basin planning, with an emphasis on water allocation and drought vulnerability assessment (Andreu et al., 1996). To ensure that approved plans provided acceptable levels of drought vulnerability, indicators and criteria about acceptable and unacceptable values were agreed in a participative process since 2004.

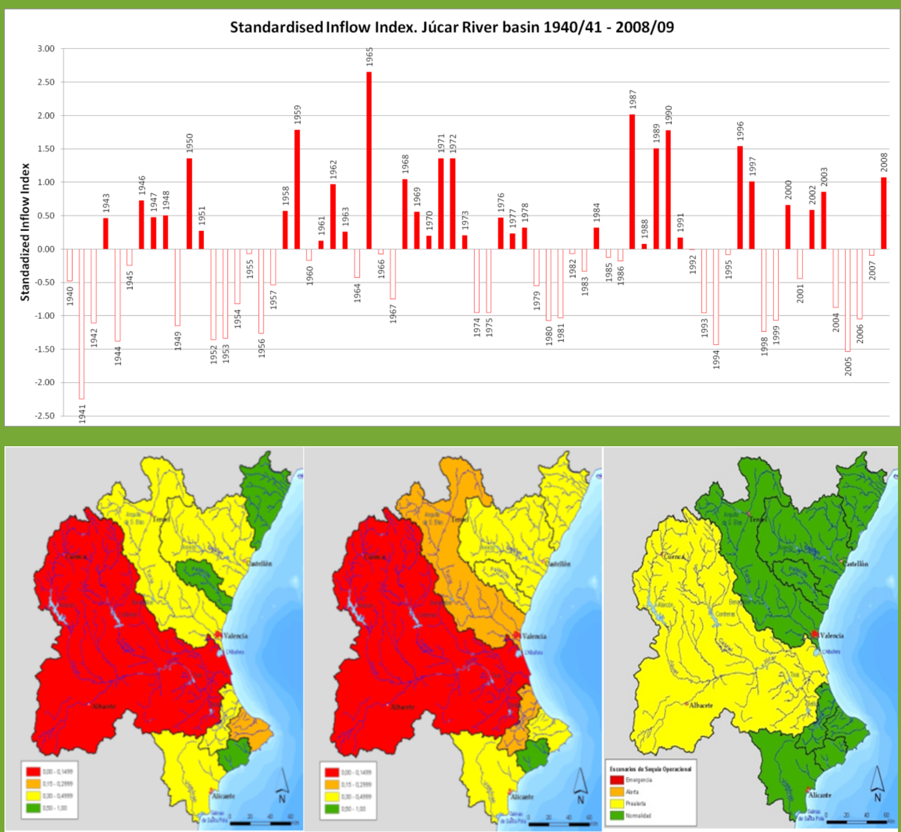
In parallel, from the year 2000, the JBPPP adopted a clearly proactive approach by developing a Special Drought Management Plan (SDP) (Estrela and Vargas, 2012). A Composite Drought Operative Index (CDOI) (Ortega et al., 2015) was introduced to monitor drought states (normal, pre-alert, alert and emergency). CDOI maps are published regularly (Figure 3.46) and serve as early warning to trigger predefined anticipation and mitigation measures attached to each drought state. The final DSS, which has been regularly updated, was accepted by all parties as a reliable tool for planning scenarios (Andreu et al., 2009). It includes a probabilistic approach (Andreu and Solera, 2006) to obtain more specific risk assessments (e.g. probabilities of deficits and reservoir states at short and medium timescales, the impact of anticipation and mitigation measures) (Andreu el al., 2013). Anticipation and mitigation measures include: (1) more efficient water use, (2) water saving, (3) conjunctive use of surface and groundwater, (4) financial compensation for giving up water use, (5) water rights purchase for environmental protection, (6) irrigation sluice water recirculation, (7) reuse of waste water, (8) enhanced control of water use, water quality and the ecological status of water bodies, and (9) revision of actions and post analysis. In the alert and emergency state, the JBPPP Participatory Permanent Drought Commission (PDC) has special powers, for example to override water rights and priorities, to further improve governance aspects, thereby facilitating consensus for equitable decisions.

The JBPPP PDC demonstrated its relevance during the severe 2004-2008 drought (Andreu et al., 2013). The governance body had 28 sessions with successful results, as recognised by its own stakeholders (Urquijo et al., 2016). It provided transparency and credibility to the decision and policymaking processes. Drought management and planning in the JBD is internationally recognised as exemplary (e.g. Schwabe et al., 2013; Kampragou et al., 2015; Wolters et al., 2015).

Nevertheless, improvements can still be made, for instance through: (1) refinement of monitoring of indicators and real-time data gathering, (2) the consolidation of measures, (3) further enhancement of institutional and legal aspects, (4) demand and supply management, and (5) the use of additional economic instruments (e.g. insurance for irrigated agriculture). Finally, major challenges have been maintaining the personal commitment of individuals in all sectors (knowledge brokering, policymaking, NGOs, stakeholders in general) and incorporating the comprehensive interaction in the regular functioning and procedures of the institutions and other bodies involved.

FIGURE 3.46

The Jucar Basin (south-east Spain). Standardised Inflow Index for the JBD (left), and CDOI maps corresponding to March 2006, January 2007 and March 2009 (right, from left to right).
Source: self-elaboration from public domain information.



3.10 Climatological risk: wildfires

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3.10.1 Introduction – wildfires in the context of natural and man-made hazards

About 4 % of the global vegetated area is burnt every year by fires (Giglio et al., 2013; Hantson et al., 2015). Wildfires have significant impacts on humans and on the natural environment. They affect human lives and livelihoods (Finlay et al., 2012) and result in high social and economic costs, associated not only with the damages, but also with the prevention and suppression measures put in place every year (Birot, 2009). Fires cause large increases of atmospheric emissions and pollutants (Carvalho et al., 2011), cause soil erosion (González-Pérez et al., 2004), reduce the provision of goods and services by forests (Mavsar et al., 2013), and change land cover patterns and landscape ecosystem dynamics (Moreira et al., 2011; San-Miguel-Ayanz et al., 2012).

Wildfires, which are often caused by humans, have a large impact on human assets and the natural environment, contributing to atmospheric pollution and reducing the provision of goods and services from forests and other ecosystems.

Wildfires are commonly considered natural phenomena for many ecosystems, as wildfire ignition and spread are greatly driven by vegetation and meteorological conditions. However, humans have used fire for land use management and hunting for at least the past 100 000 years (Bowman and Panton, 1993). Nowadays, human-caused wildfires have become a major hazard for the environment and human assets globally. An analysis of fire causality in Europe shows that more than 95 % of the fires in this region are caused by negligence or arson (Ganteaume et al., 2013). Likewise, an analysis of fire causality worldwide shows that most wildfires are caused by humans (Krawchuck and Moritz, 2011).

However, although wildfires are most often initiated by human actions, their intensity and their effects are mainly driven by fuel condition and availability, vegetation structure (Gonzalez-Olabarria and Pukkalaet, 2011) and prevalent meteorological and topographic conditions. In the context of this subchapter, wildfires are considered a natural hazard, regardless of their ignition source.

3.10.2 Wildfires – definitions

Definitions of wildfire vary according to the scientific or operational context in which the issue is discussed. Until recently, in Europe, the most commonly used term to define and discuss wildfires that are not the result of a controlled human activity (these would usually be called 'prescribed fires') was 'forest fire'.

This chapter uses the term 'wildfire', as it is more general than the term 'forest fire' and includes fires that affect other vegetation types such as grasslands, shrublands and other non-forest land covers.

A forest fire, according to EU regulations (EC, 2003) is a fire that starts in any land cover and spreads to affect forest areas, these being forests as defined by the FAO (1998). However, the term 'wildfire' is more general than that of forest fire and includes fires that affect other vegetation types different from forests. This term is thus more applicable to fires that affect grasslands, shrublands and other non-forest land covers.

3.10.3 Wildfire risk

3.10.3.1 Definition

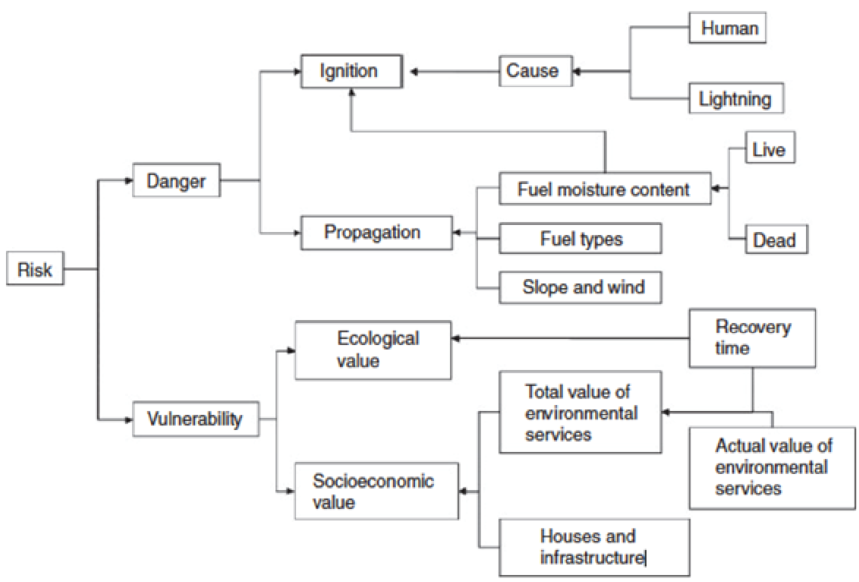
The definition of risk used by the IPCC's special report Managing the risks of extreme events and disasters to advance climate change adaptation (2012) is that risk is a function of hazard, exposure and vulnerability. This subchapter uses these terms as key components of the wildfire risk. In other fields, such as the prediction of droughts or earthquakes, risk is often considered as the conjunction of two factors, namely the hazard, or potential threat to humans and their welfare, and the vulnerability, or exposure and susceptibility to losses.

Traditionally, wildfire risk has been assessed at national or local scales using individual data sources and methodologies. This has led to local or national indices that are not comparable either across Europe or worldwide. In addition, there are differences of opinion over the definition of fire risk. According to the FAO's terminology (FAO, 1986), forest fire risk is 'the chance of a fire starting as determined by the presence and activity of any causative agent'. The Vocabulary of Forest Fire Terms compiled by the DELFI forum (1999) supports this definition, stating that fire risk is 'the probability of fire initiation'. Other approaches consider wildfire risk as 'the potential number of ignition sources' (Hardy, 2005). It should be noted that fire ignition is not the same as fire initiation, since not every ignition outbreak develops into a fire.

Other authors suggest wildfire risk to be the probability of wildfire occurring at a specified location, and under specific circumstances, together with its expected effects (San-Miguel-Ayanz et al., 2003). Wildfire risk has also been defined as 'the probability of a fire to happen and its conse-

FIGURE 3.47

Proposed framework for an integrated fire risk assessment system
Source: adapted from Chuvieco et al. (2010)



quences' (San-Miguel-Ayanz, 2002), following the general UNISDR terminology of risk (UNISDR, 2009), while other definitions consider that fire risk is 'the union of two components: fire hazard and fire ignition'. In this case, the overall risk depends on the fuel and its susceptibility to burning (i.e. hazard), and on the presence of external causes (both anthropogenic and natural) leading to fire ignition and spread.

Wildfire risk is derived from the combination of fire hazard and fire vulnerability, namely hazards related to the presence of fuels and ignition sources, and vulnerability related to the assets at risk.

The international standard on risk management, ISO 31000, defines risk as the 'effect of uncertainty on objectives'. For this definition of risk, there needs to be a clear objective, for example, avoiding significant human impacts from wildfires. Recent studies at the local and global levels describe wildfire risk as being derived from the interaction of two components, fire danger and vulnerability. In this case, fire danger is equivalent to fire hazard (see Figure 3.47).

3.10.3.2 Components

Considering the most recent definition above, fire hazard can be defined as the combination of the presence of ignition sources, fuel availability and conditions for fire ignition and spread (fire behaviour) (Oliveira et al., 2014). It thus refers to the conditions under which an ignition can result in a wildfire, as a result of the availability of fuels and their condition, and the prevalent meteorological conditions. Vulnerability refers to the susceptibility of suffering damage. This term is often associated with exposure, as vulnerability exists if a series of assets (such as lives or property) are exposed to damage by wildfires (Galiana-Martín and Karlsson, 2012). This approach is consistent with the ISO 31000 standard.

3.10.4 Existing knowledge and the issue of scale in fire risk assessment

Wildfires are a recurrent phenomenon, and their importance in the earth system is widely recognised (Dwyer et al., 1999; Bowman et al., 2009; Flannigan et al., 2009; Scott et al., 2016). Wildfires affect many regions in the world and their impacts are evident in natural systems and human society.

Owing to the many factors that affect fire risk, the issue of scale is highly relevant in the assessment and management of risk. At local to national scales, the assessment of wildfire risk is accompanied by mitigation measures aimed at reducing fire risk by increasing prevention and preparedness. At the supranational and global scales, assessment aims to reduce the negative impacts of wildfire by establishing international guidelines and agreements for best practice among the wildfire management organisations. Organisations such as UNISDR seek to establish common nomenclatures and methods for the assessment of risks. At the European level, an initiative to compile information on National Risk Assessment good practice is currently ongoing. An analysis of the resulting data will provide guidelines on good practices for the assessment of wildfire risk in Europe and, probably, at the global scale.

Although there is a vast knowledge of wildfire risk-related issues, information varies according to the scale at which risk is assessed, varying notably from local to regional or global scales.

Therefore, the involvement of so many organisations in fire management, from national to local level, means that clear definitions of authority, functions, tasks and responsibilities, together with an effective coordination of their inputs is essential. The influence of the multilevel governance structure is a key issue in wildfire management (Aguilar and Montiel, 2011).

3.10.5 Wildfire information systems: regional, national, global

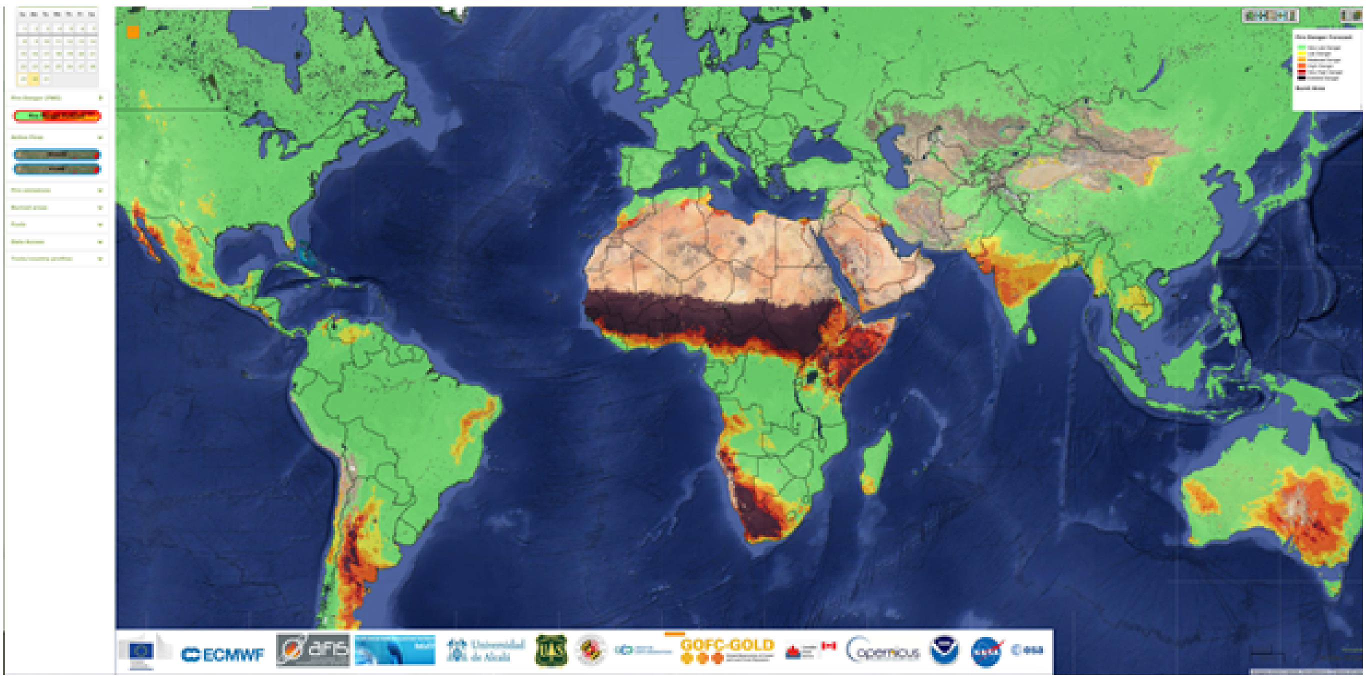
Often, fire management is the responsibility of local to regional agencies within a country, although these operations are commonly supported by national governments. In developed countries, the increase in the number of human-caused fires and the large economic losses caused by them have triggered forest fire prevention and, in particular, firefighting programmes.

A range of infrastructural components including hard infrastructure (e.g. control centres), plus education and awareness raising (strategic as well as tactical or responsive) are part of permanent programmes. Moreover, expenditure in firefighting equipment and operations has escalated in recent decades, especially with the increasing use of aerial firefighting.

As technology has evolved in the last decade, modern methods for the analysis of fire risk components and the evaluation of fire effects have found their place in national, regional and global organisations. Accordingly, wildfire information systems often include modules for the dynamic evaluation of fire danger and the frequent update of fire risk components such as fuel distribution, structure and moisture content. Satellite technology and Geographic Information Systems permit the integration of spatial layers of information to analyse spatial patterns of fire occurrence and to derive fire risk at different scales. National fire information systems to assess and quantify fire risk exist in nearly all European countries, although they differ in approach. Regional initiatives of wildfire information systems are the European Commission's European Forest Fire Information System (EFFIS) and the recent Group on Earth Observations (GEO) initiative to establish a Global Wildfire Information System (GWIS) (see Figure 3.48).

FIGURE 3.48

The North American Drought Monitor
Source: HELIX project (Naumann et al., 2017)



Both initiatives are currently under the umbrella of the EU Copernicus Regulation. These systems benefit from other initiatives aimed at deriving relevant information, such as the Climate Change Initiative of the European Space Agency (ESA).

3.10.6 Wildfire management: prevention, preparedness, impact assessment, restoration

The wildfire policies adopted by most European countries over the last century have been based on fire exclusion regardless of their specific context. Nowadays, this approach is widely recognised as being neither ecologically desirable nor economically feasible. Total fire exclusion policies have significant consequences for the magnitude and frequency of wildfires, through an increase of fuel accumulation, the loss of resilience to fire and the alteration of fire regimes. New approaches to wildfire defence are required to improve the strategies of prevention and suppression (Montiel and San-Miguel, 2009). A further step is given by the concept of integrated fire management (Sande Silva et al., 2010). It involves the consideration of the various aspects of fire in suppression and prevention as well as the use of fire as a tool for management practices.

An integrated system for wildfire management must consider the different phases of the fire cycle. According to the definition of fire risk in the sections above, wildfire management requires the monitoring of all the factors that affect fire ignition, spread and impact. It also requires action to prevent and mitigate fire impacts. Fire prevention must target the reduction of fire ignitions as well as the management of fuels, as these are the only factors affecting fire propagation upon which we can act. Whenever the fire exclusion policy is predominant, this fuel management is commonly restricted to reducing fuel spatial continuity, by fuel breaks, or fuel amount using grazing or mechanical means. Those fuel reduction operations can be eventually used for the generation of biomass energy. In many regions, the result of the fire exclusion policy is often the continuous accumulation of fuel, which, when ignited, can result in uncontrollable wildfires (San-Miguel-Ayanz et al., 2013; Viegas et al., 2009). However, prescribed burning is not widely accepted in many countries, particularly because of potential accidents and negative public perception. Policy conflict between different government departments occurs in other areas, for example in the conversion of land for certain forms of wildlife habitat such as heathland, and housing development on land surrounded by vegetation at significant risk of ignition. It is important that these conflicts are worked through and resolved.

Since most fires are caused by humans, fire prevention activities require measures to prevent these ignitions, which can be the result of negligent behaviour or criminal actions. This implies the implementation of education programmes in rural areas where the fires take place. In many places, it is necessary for these to be dynamic and recurrent. Fire is a common tool in agricultural management and the elimination of these practices can be difficult to achieve without significant trade-offs. In some countries, government strategies tend to focus on cooperation with rural populations in the safe implementation of prescribed fires (Montiel and Kraus, 2010). In other countries, fire is still used as the main tool to convert forested areas to agricultural or pasture land. Regarding criminal actions in relation to the widespread deliberate burning to clear rain forest, for example in Indonesia and Brazil, strategies for cooperation with the local population and legal actions must be put in place.

Wildfire management comprises the totality of the fire cycle, before the events in the prevention and preparedness phases and the post-fire assessments that lead to the implementation of restoration measures.

Preparedness refers specifically to activities in the period immediately before fire initiation, notably at times of the year when fire hazard is greatest. Modern technologies for the assessment of vegetation dynamics and meteorological weather prediction systems allow forecasting of fire danger conditions, resulting in enhanced preparation for firefighting. The use of remote sensing techniques has become common among forestry and civil protection organisations. Remote sensing permits the near-real-time assessment of fire spread, which can be used in decision-making for the deployment of firefighting crews and equipment during large wildfire events. Remote sensed information is also used to assess fire effects at a very low cost, which complements necessary field campaigns for the in situ assessment of damage and the planning of restoration measures.

3.10.7 Other hazards such as windstorms and pests and their relationship to wildfire risk

Other natural hazards that worsen the conditions for wildfire management often result in an increase in the levels of fire risk.

Prolonged droughts (see Chapter 3.9) and heatwaves (see Chapter 3.8) dry out fuels and help to create the conditions for uncontrollable wildfires (Gower et al., 2015). Examples of these are the fires that occurred in 2003 in Portugal and southern France, and in 2007 in Greece. Windstorms can result in the sudden accumulation of large amounts of fuel, which are often difficult to manage or extract. Furthermore, the difficult arrangement of fuels on the ground hinders the effective implementation of fire prevention measures and hampers firefighting operations. Examples of these situations occurred in the areas affected by Storm Gudrum in Denmark and Sweden (2004), which resulted in the world's largest stockpile of wood (de Rigo et al., 2016), and Storm Klaus (2012) in France.

In Europe, heavy attacks by insects and phytopathogens can have major impacts on forests, resulting in reduced forest health and, sometimes, widespread tree death (FOREST EUROPE, 2015). Standing dead timber poses an increased risk of wildfire. The loss of economic value may induce lack of fuel management and increase the fire risk. The accumulation of dead and fallen woody fuel following windstorms (see Chapter 3.7) also makes these forest areas more prone to attacks by insect pests and further increases their vulnerability to wildfire.

Other hazards, such as pest outbreaks or windstorms, may increase wildfire risk and hamper wildfire prevention measures.

However, wildfires can also influence other hazards. They are particularly shaping the flood scenarios in the fragile Mediterranean-type ecosystems, where the peak flood and the suspended material load of water streams increase significantly in post-fire conditions, inducing soil erosion, floods and landslides.

3.10.8 Harmful effects of wildfires on human population and health

The effects of wildfires include damage to land cover, which encompasses the loss or degradation of natural values and the decrease or failure of provision of ecosystem services in the affected areas, which can be temporary or permanent. These include, among other things, soil protection, water purification, recreation, tourism, etc.

In addition, wildfires emit large volumes of gases that affect the human populations in the areas affected by them. Wildfire emissions contribute considerably to the total global atmospheric carbon emissions and are a concern from local to global scales. At the global scale, assessment of emissions is compiled in the Global Fire Emissions Database - GFED (Randerson et al., 2015).

In addition to economic and environmental damage, wildfires pose a serious threat to human populations, producing negative effects on human health and increasing death tolls.

At the local scale, wildfire emissions can have harmful effects on the local population (Finlay et al., 2012; Bowman and Johnston, 2005). The effects of atmospheric pollution by wildfires include the aggravation of respiratory problems in the population and can result in the deaths of more susceptible individuals. Serious problems to human health were recorded in many critical fires during the last decade; possibly the most noted events were those in Indonesia and Russia in 2010 and Indonesia in 2015. The Indonesian fire event in 1997 resulted in an estimated 45 000 km^2 of forest and land being burnt on the islands of Sumatra and Kalimantan, releasing between 0.81 and 2.57 Gt of carbon to the atmosphere, equivalent to 13–40 % of the mean annual global carbon emissions from fossil fuels. As a result of this fire, an estimated 20 million people in Indonesia suffered from respiratory problems, with 19 800-48 100 premature mortalities (IFFN, 2000). Russia reported a death toll of about 700 people daily in connection with the smoke problems caused by peat fires in the Moscow region in 2010 (The Guardian, 2010). Less well known is the significant psychological effect that some people can experience after close contact with wildfire (Eisenman et al., 2015).

3.10.9 Contextual factors affecting wildfire risk

3.10.9.1 Climate change

Currently, an average of 400 million ha of natural areas are burnt annually at the global level (FAO, 2015: 245). Many organisations, including the IPCC (2014) contribute to the assessment of the relationship between climate change and fire occurrence, supporting wildfire prevention in the context of global change. A number of researchers have highlighted the potential changes in fire climate regimes in different parts of the world, which may result in increased fire risk and exacerbation of the effects of wildfires, especially in the Boreal and Mediterranean climatic regions (Barbero et al., 2015). Climate studies in Sweden show that more fires, especially in south-east Sweden, with a fire season that is about two times longer than the current fire season, is expected, with attendant climate change scenarios (Sandahl, 2016).

The effect of climate change in the United States (Westerling et al., 2006) has already led to an increase in large-fire activity in the western United States, with longer wildfire duration and longer wildfire seasons. Likewise, climate change is associated with an increased fire danger and consequent larger burnt areas in the EU Mediterranean region by the end of the century (Amatulli et al., 2013; Khabarov, et al., 2014). The increase in fire activity and burnt areas will consequently lead to an increase in fire emissions in Europe and globally (Jolly et al., 2015). The economic impact of climate change, including the effects of wildfires, has recently been assessed in the context of the Peseta II project of the JRC (Ciscar et al., 2013).

3.10.9.2 Socio-spatial factors of wildfires: population, land cover and land use change, and landscape dynamics

Socio-spatial factors have a major role in the management of wildfire risk. As noted in the literature, there is a proven relationship between ignitions and human populations (Bowman et al., 2011). Furthermore, the increase in the intensity of wildfires results every year in a number of human casualties and large economic losses due to the destruction of human assets (San-Miguel-Ayanz et al., 2013; Viegas, et al., 2009; EM-DAT, 2009). The expansion of the so-called Wildland Urban Interface (WUI) leads to an increase in wildfire risk and to the much more difficult management of wildfires. Often, fire-fighting crews must protect human assets and disregard the fighting of wildfires, limiting their intervention to the protection of human lives and properties.

Wildfire risk is affected by contextual factors. The main factors are climate change and socio-spatial factors such as population, land cover and land use change, and landscape dynamics.

The changes in land cover and land use patterns due to the movement of population from rural areas to urban centres in many parts of the world, and the consequent decline in fuel management in these areas, leads to an increase in fire risk and higher intensity of wildfires (San-Miguel-Ayanz et al., 2012).

Wildfires are a complex socio-spatial

issue. However, both systemic components – space and society – have usually been dealt with separately. The spatial patterns of wildfires have been analysed at the regional scale, using the available data and employing methods of comparative analysis for producing an overview of fire occurrence in Europe (Chas-Amil et al., 2015; Montiel and Herrero, 2010; Salis et al., 2014). Interesting literature on the spatial distribution of fire occurrence has also been developed at the municipal level (Fernandes, 2016; Martínez-Fernández et al., 2013). The social aspects, which are basically related to community-based fire management and community wildfire relations beyond wildland fire causes and wildland fire defence organisation, are less well known.

The temporal patterns and the evolution of the spatial patterns through history have also been less studied, owing to data limitations. The temporal dimension of wildland fires has been mainly explored in the short term, considering the different periods of the existing statistical series, although some studies have analysed fire history on the basis of lake charcoal deposits from the last 12 000 years (Whitlock and Larsen, 2012). The interactions between environment factors, the social context and the fire regime over the long term, as well as changing fire behaviour spatial patterns, resulting in the creation of new territories at risk, are still largely unknown. Furthermore, it is essential to take into account the territorial contextual factors (land cover and land use, meteorological factors, land tenure, cultural and organisational aspects, public policies) that interact and influence fire occurrence to better understand wildland fire causes (Beilin and Reid, 2015; Montiel and Galiana-Martín, 2016).

The interactive evolution of spatial and human issues is defining different land-type fire scenarios at various scales. The concept of fire scenario (Montiel and Galiana-Martín, 2016) has provided an important conceptual foundation by which to understand connections between landscape patterns and dynamics and fire behaviour (propagation patterns). The use of fire scenarios is thus useful to establish fire-design management strategies at the landscape level (Costa et al., 2011; Moreira et al., 2011) that increase social and ecological resilience and reduce territorial vulnerability to fire risk. Figure 3.49 shows a fire-resilient Mediterranean landscape in Sierra de Gata (Spain), in which diversified land management and fuel discontinuity prevent high-intensity wildfires.

FIGURE 3.49

Wildfire- resilient Mediterranean landscape in Sierra de Gata, Spain. Source: photo courtesy of C. Montiel

3.10.10 Innovation for better understanding and wildfire management

Innovation in wildfire management comes from two main sources: (1) operational experience, in a lessons learning process, and (2) scientific research. Such knowledge and innovations are incorporated in the management activities through, for example, the advancement in methods to quantify and map fire risk components and the incorporation of human factors in the management of wildfires through education campaigns, rural programmes and a better consciousness of human society on the impacts of wildfires. However, there remains a lack of agreement with national and regional fire administrations on the implementation of a common wildfire risk assessment at the European or global levels.

Relevant progress has been made in the implementation of common methodologies to assess fire danger at the European level in the context of EFFIS. At the global level, there are initiatives to promote the production of information that forms the basis of wildfire risk assessment (GWIS, FIREGLOBE, 2008), such as global fuel maps (Pettinari and Chuvieco, 2016), global fire ignition sources datasets, global fire vulnerability (Chuvieco et al., 2014), as well as global burnt area maps (Chuvieco et al., 2016). In addition, global data on fire ignitions and burnt areas are provided by the National Aeronautics and Space Administration FIRMS activity and fed into regional and global systems (e.g. AFIS, INPE, GWIS).

Innovation in wildfire management involves the adoption of new technologies for the assessment of wildfire risk and the incorporation of the human component in the implementation of prevention measures.

Some of the areas in which innovation can be further developed are as follows:

- Increased use of fire spread models, coupled with portable, hand-held devices to make decisions on site during firefighting (SCION, 2009).
- Increased use of digital technologies and social media to reach relevant stakeholders and lay communities at times of heightened fire risk; use of these platforms to get early warnings of wildfire outbreaks (two-way knowledge exchange).
- Increased synergy between different agencies and departments with responsibility for disaster management. Economies of scale and greater effectiveness in bringing relevant parties/actors together when it matters. This is important for countries such as the United Kingdom, where the risk of storm and flood damage is currently much greater than the risk of wildfires. Working together is likely to engender a better understanding of the impending wildfire problems that climate change is already bringing about — a significant form of preparedness.
- A better integration of the four 'R's (risk reduction, readiness, response, recovery) with shared responsibilities between land managers/owners and the civil contingency community.
- A better understanding that prevention is better than cure (e.g. Firewise (NFPA, 2016)), especially in times of recession when government agencies are being cut back. Hence, land managers are being brought into the risk management process via wildfire fora, projects and other forms of communication. Government financial incentives for forest management (grants) are also manipulated to ensure that applicants understand the need to embrace wildfire risk-reduction policy and practice (GOV.UK, n.d.).
- Increased rooting of government policy in a risk-based framework (HM Tresaury, 2013), driven by climate change and other national risks (e.g. in a National Risk Register (Cabinet Office, 2015)). Better understanding that poor handling of a disaster can be politically damaging in a digital environment when blame can be ascribed with some confidence (Gasper and Reeves, 2011).
- Increased use of the ecosystem framework (e.g. Millennium Ecosystem Assessment - MEA, Mapping and Assessment of Ecosystems and their Services - MAES) to contextualise ecosystems, their goods and services and their values (e.g. via Natural Capital Accounting (BISE, n.d.)), and thus the potential loss from wildfire; e.g. the ecosystem approach has been used to evaluate potential loss from wildfire in a study in the United Kingdom (KWFW, 2014).
- Disaster Management degree (BSc, MSc) courses will help to embed risk analysis in the mainstream.

3.10.11 Research gap

Although innovation provides a better assessment of fire risk components, and research demonstrates the applicability of research methods in pilot projects, there is still a lack of proof-of-concept at an operational level.

Few of the research advances in projects are adopted or implemented by regional or national administrations. This is often due to the complexity in the use of new tools and the inertia of these administrations to change the use of long-established methods, which are well known by staff.

Basic research on the social aspects of wildland fire is very limited. The existing literature is mainly applied research, in particular case-studies of certain aspects of the social dimensions of wildland fires (wildfire human causes and influencing factors; fire laws/policies/regulations; fire management; socioeconomic impacts of wildfire risk; social awareness/vulnerability/resilience to wildfire risk, etc.).

Although progress has been made in the assessment of fire risk components, there is still a need for research on, inter alia, fire risk and behaviour models as well as policy, social and economic aspects.

In general, these scientific publications are analytical descriptions used to assess a specific issue of wildland fire factors or impacts at the local or regional level, instead of the community one which is closer to the social approach because this is the scale at which people organise and interact.

Research is needed in both technical and social spheres. It is easy to predict that developments in wildfire risk management will follow the increase in sophistication and use of digital technologies. These largely support the readiness, response and recovery phases in disaster management. However, it is less easy to be sure that reduction via a decrease in ignition events can take place without significant changes in human behaviour for which social research will be valuable.

The following are a few areas of research that could be prioritised (not in order of importance):

- Refinement of risk models (continual process), based on developments in fire science and better parameterisation, for example based on increased knowledge of vegetation, its phenology and flammability. This will be achieved through basic experimental research, monitoring and modelling.
- Modelling of wildfire risk in the context of predicted land-use change, which is affected by a range of social, economic and environmental (e.g. climate change) drivers. Foresight analysis is very important.
- Gaining a better understanding of wildfire behaviour to support fire prevention and fire suppression activities and to improve fire safety. The development of more advanced fire suppression methods to cope with very high-intensity fires that are becoming more common.
- Economic analysis of wildfire consequences, including all elements of risk management (reduction, readiness, response, recovery) at a regional or national scale in order to evaluate cost-effectiveness of investment in each of these elements. This must include the value of loss of the full range of ecosystem goods and services.
- Land use/cover analysis (both current and future projections) that would better characterise the impacts of landscape structure in fire propagation.
- Policy analysis to understand at national/international levels how wildfire policy can work synergistically with existing agricultural, forestry, urban and habitats/biodiversity policies instead of conflicting with them. Use of ecosystems frameworks to explore trade-offs and provide possible ways forward.
- Social research to understand the perceptions of wildfire risk in the different land management sectors and the constraints to adopting a more realistic approach to it. In other words, why do we still experience so much negligent behaviour? Research to find ways to overcome such obstacles should be undertaken.
- More social research to understand why people commit intentional fires, and how to reduce these motivations and to have a larger involvement of the population in the fire prevention and risk-reduction activities. A better understanding of the interactions between physical and human factors affecting fire ignition is needed.

3.10.12 Partnerships and networks, international collaboration in wildfire management

International collaboration in wildfire management exists in different fora. There are networks that have collaborated to establish common wildfire management practices among countries. For instance, the Voluntary Guidelines: Principles and Strategic Actions of the FAO provide a series of recommended practices for wildfire management (FAO, 2006). These have been adopted by many countries, including most EU Member States.

There are bilateral agreements among many EU Member States for fire prevention and, in particular, for firefighting. In addition, at the European level a general agreement for collaboration exist between countries to share firefighting resources during fire campaigns. This agreement is established under the so-called Union Civil Protection Mechanism (UCPM) and is coordinated by the European Commission's ERCC.

At the global level, one of the most long-lasting initiatives aimed at building and retrieving information on wildfires is that of the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) Fire Implementation Team. This brings together researchers and regional networks to generate and analyse information on wildfires at different spatial scales, as well as to develop new methods for wildfire monitoring, management and policy decision-making. The synergies between this network and the GEO Global Initiative on establishing a GWIS may result in improved access to wildfire management information globally.

Regarding community-based cooperation, organised groups of local stakeholders are emerging, especially in Mediterranean countries. These groups contribute to fire management as a result of instrumental motivation, or self-interest (Aguilar and Montiel, 2011).

3.10.13 Conclusions and key messages

There is a vast amount of information on wildfires at local, regional and global scales. However, problems remain at different scales in terms of harmonising or standardising practices for the assessment and management of wildfire risk.

Resilience theory is providing a suitable framework by which to explain abrupt changes in socioecological systems. The importance of community participation and building social capital through collective learning and governance mechanisms has been highlighted as a required basis for building disaster resilience (Aldunce et al., 2015; Aldunce et al., 2016; Montiel and Kraus, 2010; O'Brien et al., 2010). Another relevant contribution of the resilience theory to fire risk mitigation is the capacity to anticipate, prepare and plan (Aldunce et al., 2015), which is one of the theoretical foundations of the concept of fire scenarios. In fact, understanding the role of fire on the landscape and the influence of landscape on fire regime is crucial for the resilience of territories to wildfire risk.

Cognitive hierarchy theory is also a strong theoretical foundation of social learning processes that may enable a reduction in ecological and social vulnerability to wildfire, particularly at the WUI (Galiana-Martín and Karlsson, 2012; O'Brien et al., 2010). Nowadays, one of the most important factors that affect wildfire impacts (and adds risk to humans) is the expansion of the WUI. Considering that the developments in fire policy, in terms of environmental politics, depend on the social construction of fire problems (Hajer, 2000), the social perception of fire risk and fire culture are crucial components by which to understand and enhance support for specific management strategies (Czaja and Cottrell, 2014). This is one of the bases of social prevention programmes for reducing unwanted ignitions, including the promotion of good practices of fire use (Montiel and Kraus, 2010).

The following recommendations would help to enhance fire risk management from local to global scales in relation to three aspects, namely partnership, knowledge and innovation.

Partnership

Engaging the wildfire community with other involved groups in other areas of disaster management or emergency response in order to build on synergies and best practice methodologies.

Engage the lay public and land management sectors, as a unified and non-contradictory 'voice' is vital — confusion always leads to disinterest and failure of communication.

The exchange of research outputs, models, best practice and experience between countries should be encouraged through the continuation of existing international forums and other mechanisms (e.g. Marie Curie and Erasmus programmes in the EU); this is especially important for countries with less experience of wildfires to learn from those with more experience, particularly in the context of climate change.

Wildfire governance schemes are urgently needed in order to obtain consensus between the different stakeholders to create collective willingness and favour the effectiveness of wildfire management systems. It is important to identify the institutions/administrations that are relevant for the implementation of actions related to wildfire risk assessment/mitigation.

Cooperation between the competent authorities and rural communities for wildfire preparedness and damage mitigation should be enhanced through organisation assistance, equipment supply and training sessions for locals. Good governance in wildland fire management requires the conscious regulation of fire use practices and the establishment of an action protocol to arrange cooperation for pre-extinction measures and emergency responses between the different stakeholders.

The wildfire community should engage with world-changing agencies such as the IPCC to ensure that its voice is heard, and that planning for the future takes wildfire risk fully into account. It may be that there are currently too many competing international wildfire bodies, which need to find ways of integrating together as individually they are too small. The IPCC is an example of what can be achieved using a good platform.

Knowledge

Harmonisation or standardisation of practices for the assessment and management of wildfire risk across Europe or at global scale has merit. However, it is more important to reach a common scientific understanding and to facilitate individual countries to deploy such knowledge/wisdom in the best way for the particular needs of the country.

It is necessary to identify if harmonisation is possible for all European countries, or if this would be appropriate only for countries with similar climatic conditions. The same approach should be considered worldwide.

When dealing with harmonisation/standardisation, it is important to identify what needs to be harmonised. This is possible for example for the definition of wildfire and wildfire risk, information systems, actions to take for wildfire management, capacitation of resources, education and information messages during fire campaigns.

Social education and prevention programmes, which aim to increase knowledge of wildfires and to reduce unwanted ignitions, are essential where fire is a traditional land use and resource management tool.

Innovation

Technical research is important but, using current knowledge to the fullest effect, effort must be put into engagement with politicians and senior decision-makers in order to ensure that wildfire management is given strategic support and is resourced appropriately.

Integrated fire management is an innovative concept to reduce damage and maximise the benefits of fire. It includes a combination of prevention and suppression strategies and techniques that integrate the use of technical fire and regulate traditional burning.

Fire scenarios are a new tool for integrating fire management and land use planning to reduce the vulnerability of territories and societies to wildfires. The concept of a fire scenario is useful when confronted with the need to coexist with fire but this requires an understanding of societal discourses and risk constructs at the landscape scale. This innovative approach to fire management provides arguments for adapting land use and forestry practices to the changing fire hazard.

3.11 Biological risk: epidemics

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3.11.1 Introduction

An epidemic is the widespread, and often rapidly extending, occurrence of an infectious disease in a community or population at a particular time (CCDM, 2008). A pandemic is the extension of an epidemic to many populations worldwide or over a very wide area, crossing many international boundaries and affecting a large number of people (Last et al., 2001). Both epidemics and pandemics can be hugely disruptive to lives, livelihoods, and the political and socioeconomic stability of affected communities. As a result of this capacity for disruption, they constitute a class of disaster, which like other types of disaster, presents risks that can be ameliorated or reduced through risk management. As a class of disaster, epidemics and pandemics possess some unique characteristics. Infectious disease pathogens continue to circulate, extend and evolve during an event and thus present ongoing and changing challenges in regard to assessment, impact and persistence, further complicating risk management, control and recovery (Floret et al., 2006). For example, the emergence of antimicrobial resistance may thwart efforts to effectively treat infectious disease, resulting in more costly health care as well as prolonged illness and mortality.

Unless detected and controlled at a very early stage (when this is possible), epidemics are prolonged, and pandemics more so. Robust and sensitive systems for detection and surveillance therefore form the backbone of risk management strategies.

While many endemic or routine infections have been controlled in developed countries by immunisation, antimicrobials and improved standards of health and nutrition, they may still pose major hazards in developing countries with weaker health systems, fewer resources to devote to health and limited access to care. Such health systems are also poorly equipped to withstand epidemics of emerging infectious diseases, which may be sporadic and far more difficult to predict, and often involve diseases for which there is no cure (Jones et al., 2008). The existing routine surveillance systems may not be able to detect early signs of outbreaks. As many of the severe emerging diseases (such as Ebola, West Nile, Rift Valley fever) are zoonoses, the first signs of such events may not manifest in humans but rather in wildlife or livestock, indicating the importance of strong surveillance in the veterinary sectors, and the critical value of strong linkages between human and animal health surveillance in a One Health approach (CDC, 2016a).

Disease surveillance, preparedness and response mechanisms are essential to enable any health system to respond..

Droughts, floods and other natural hazards such as earthquakes can all contribute to the initiation of outbreaks. Outbreaks of plague can follow earthquakes, as the rodents that carry plague-infected fleas are displaced from their customary habitats and food sources, and come into closer contact with human environments (Ivers and Ryan, 2006). Epidemics of Rift Valley fever often commence when a period of drought is followed by flooding or intense rainfall, so climate perturbations such as the El Niño-Southern Oscillation may herald an increased risk of outbreaks in at-risk regions, and indicate the initiation of preventive measures, such as immunisation of livestock to prevent epizootics, and heightened surveillance for early detection of outbreaks in animals and in humans (Anyamba, et al., 2001). Disruption of water and sanitation infrastructure from earthquakes, storms and floods can lead to outbreaks of water- and food-borne pathogens such as cholera (Ivers and Ryan, 2006). The extractive industries, with their attendant ecosystem disturbance, land-use and demographic changes, have been associated with precipitating outbreaks of severe emerging diseases, including Marburg haemorrhagic fever (Le Guenno, 1997). A recent study identified the top five drivers of infectious disease threats in Europe as travel and tourism, global trade, climate, food and water quality, and natural environment (Semenza et al., 2015). The implementation of measures addressing these underlying drivers could therefore be a cost-effective strategy towards reducing the risk of future disease threats.

The permanent prevention of infection has proven possible but is rare; for example, smallpox was declared to have been eradicated globally in 1979 (WHO, 1980), and the drive to eradicate polio continues to be an international priority (GPEI, 2013). Therefore, the focus is mainly on disaster risk reduction for epidemics and pandemics, which involves reducing risks in advance of an epidemic through preparedness strategies, and the mitigation of risks and hazards during the event. There are usually two general aspects to mitigating an infectious disease outbreak: the care of patients (to alleviate disease and suffering) and the epidemiological investigation of an outbreak to facilitate the response (Ferguson et al., 2006). For both patient care and the epidemiological investigation and response, the laboratory testing of human (and/or animal/vector/environmental) samples for evidence of the pathogen is important to ensure that the correct intervention strategies are employed. The magnitude of testing may be overwhelming for laboratories with specialised testing services (Kumar and Henrickson, 2012), so plans to access such laboratories should be in place before an outbreak.

The response to an emerging infection disease outbreak may initially be largely dependent on the local public health workforce but the response may soon be directly reliant on the capacity of other health departments and agencies. Again, cross-sectoral collaborative arrangements and planning for surge capacity play a fundamental role. Public health risk communication, which is effective in engaging the communities at risk and cognisant of societal and cultural values, is key to ensuring implementation and compliance with recommended public health controls. Psychosocial as well as physical consequences may also occur in epidemic response and recovery and, therefore, plans must address the management of related psychological distress and mental illness (Moore et al., 2007).

The Sendai Framework (UNISDR, 2015) states that:

"more dedicated action needs to be focused on tackling underlying disaster risk drivers, such as the consequences of poverty and inequality, climate change and variability, unplanned and rapid urbanization, poor land management and compounding factors such as demographic change, weak institutional arrangements, non-risk-informed policies, lack of regulation and incentives for private disaster risk reduction investment, complex supply chains, limited availability of technology, unsustainable uses of natural resources, declining ecosystems, pandemics and epidemics"

The framework goes on to advocate the promotion of 'transboundary cooperation to enable policy and planning for the implementation of ecosystem-based approaches with regard to shared resources, such as within river basins and along coastlines, to build resilience and reduce disaster risk, including epidemic and displacement risk' (UNISDR, 2015).

Of note, the Sendai Framework states the global target need to 'Substantially increase the availability of and access to multihazard early warning systems and disaster risk information and assessments to people by 2030' (UNISDR, 2015). The framework goes on to state that to achieve this it is important 'To enhance cooperation between health authorities and other relevant stakeholders to strengthen country capacity for disaster risk management for health, the implementation of the International Health Regulations (2005) and the building of resilient health systems' (UNISDR, 2015).

The scope of this subchapter has been limited to viral and bacterial infectious diseases only. A series of well-documented disease epidemics are summarised to demonstrate the complexity of DRM. The value of using the International Health Regulations (IHR) and pandemic preparedness approaches to disaster risk reduction on a global scale is demonstrated, innovations in Early Warning Systems (EWSs) and surveillance are discussed, and the conclusions summarise the key points and recommendations.

3.11.2 Diseases of contention

3.11.2.1 Severe acute respiratory syndrome (SARS)

The first cases of SARS occurred in China in November 2002 (Christian et al., 2004), and the disease eventually spread to 37 countries, with 8 273 confirmed cases (Chinese SARS Molecular Epidemiology Consortium, 2004). The disease caused major outbreaks in Asia and the Americas, with smaller outbreaks in Europe, illustrating how globalisation can contribute to the rapid amplification of disease spread (Coleman and Frieman, 2014). While the overall estimated case fatality rate was estimated at 15 %, the rate increased significantly with age (Chan et al., 2003). Transmission was also amplified between health workers; nosocomial transmission accounted for 72 % of cases in Toronto (Booth et al., 2003) and 55 % of cases in Taiwan (CDC, 2003).

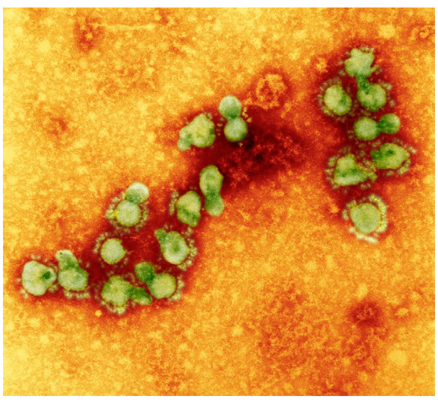
Before the SARS epidemic, coronaviruses were believed to primarily cause minor upper respiratory tract illness in humans (Myint, 1995). With SARS, illness usually begins with a high fever associated with chills and rigors, headache and malaise, followed by respiratory impairment, which, on becoming severe, requires mechanical ventilation (Peiris et al., 2003).

During the early stage of the epidemic, the non-specific presenting symptoms and the lack of access to reliable diagnostic tests made it difficult for clinicians and public health authorities to accurately ascertain cases. Furthermore, the uncertainty around the population health impacts of SARS generated considerable public fear. The need to follow up many thousands of contacts of confirmed cases to check for the development of illness placed an enormous burden on already overstretched public health services. Examples of issues identified included:

- governments investing in highly visible public health activities such as temperature testing at entry to buildings in order to provide a degree of public reassurance, with a major investment made in entry-screening at airports, even though these measures were not evidence based (Bitar et al., 2009);
- the reintroduction of enforced quarantine and isolation practices to prevent transmission, raising ethical and legal questions around the balance between public health measures and individual rights, as well as questions about the effectiveness of such measures and challenges in implementing them at scale (Huang, 2004);
- a lack of availability of hospital negative pressure isolation rooms in countries at the start of the SARS epidemic, which are required to treat ill patients safely (Gamage et al., 2005).

FIGURE 3.50

SARS
Source: PHE EDAM



Severe acute respiratory syndrome (SARS) demonstrated the need for systems for early detection and global information-sharing.

In its wake, the health-care and national economic systems of some countries were seriously disrupted. The dramatic reconfiguration of health systems in response to the epidemic, as well as the amplification of transmission in high-technology settings, caused significant disruption to normal service delivery (Wenzel and Edmond, 2003). Trade and tourism were also significantly affected, with the global cost to economies estimated to be in the region of EUR 38 billion (McKibbin and Lee, 2004). However, the basic strategy that eventually controlled SARS outbreaks worldwide was effective surveillance and containment.

3.11.2.2 Ebola

Ebola Virus Disease (EVD) is a severe haemorrhagic fever caused by viruses belonging to the genus Ebolavirus in the family Filoviridae (Gatherer, 2014). Bats are thought to be the hosts of Ebola viruses in nature, from which other wild animals such as chimpanzees and monkeys become infected (Reddy, 2015). Ebola is introduced into the human population through close contact with infected animals. It then spreads through human-to-human transmission via direct contact with the blood, secretions, organs or other bodily fluids of infected people (Feldmann and Geisbert, 2011).

Symptomatic patients experience a sudden onset of fever, muscle pain and chills accompanied by vomiting and diarrhoea, which in approximately one-fifth of cases is followed by haemorrhagic complications. In severe cases, multiple organ failure may lead to death (Hartman et al., 2010). Transmission can be interrupted through early diagnosis and the institution of effective public health measures, such as patient isolation and care, contact tracing and safe burial practices (Bausch et al., 2007).

Since 1976 when Ebola was first identified, more than 25 Ebola outbreaks have occurred in sub-Saharan Africa (Gostin et al., 2014). The recent West African Ebola epidemic (2013-16) in Guinea, Liberia, Nigeria, Senegal and Sierra Leone was the most widespread outbreak of EVD in history, resulting in 28 616 cases, of which 11 310 are reported to have resulted in death (CDCb, 2016). Owing to the collapse in the ability to deliver other essential health care, a significant rise in mortality due to other, normally treatable, disease was also observed.

On 8 August 2014, the WHO declared the epidemic a ‘public health emergency of international concern’ (PHEIC) (WHO, 2014a). Despite an understanding of the control measures required to limit the spread of the outbreak, the initial response was slow, which allowed the epidemic to gain momentum. Reasons for the slow response included the wide geographical spread of cases, the weak local health infrastructure and poor laboratory capacity to diagnose infection, the lack of expertise in containing the epidemic and treating those infected (Bell, 2016), and the delay of political leaders in calling on international assistance early on for fear of creating panic and disrupting economic activity (Moon et al., 2015). Italy, the United Kingdom and Spain were the only European countries to have imported cases of Ebola linked to the West African outbreak (WHO, 2016a).

Lessons identified from the outbreak included:

- the need for stronger event-based surveillance systems in developing countries for early detection and response, to detect and stop infectious disease threats;
- the importance of engaging local communities in the response;
- the need for stronger international surge capacity and the mobilisation of rapid assistance when countries are overwhelmed by an outbreak;
- strengthening infection prevention and control in health-care settings

FIGURE 3.51

Ebola
Source: PHE EDAM

given their potential to become 'amplification points' for spread of EVD, placing health workers at significant risk (Bell, 2016; Gostin et al., 2014).

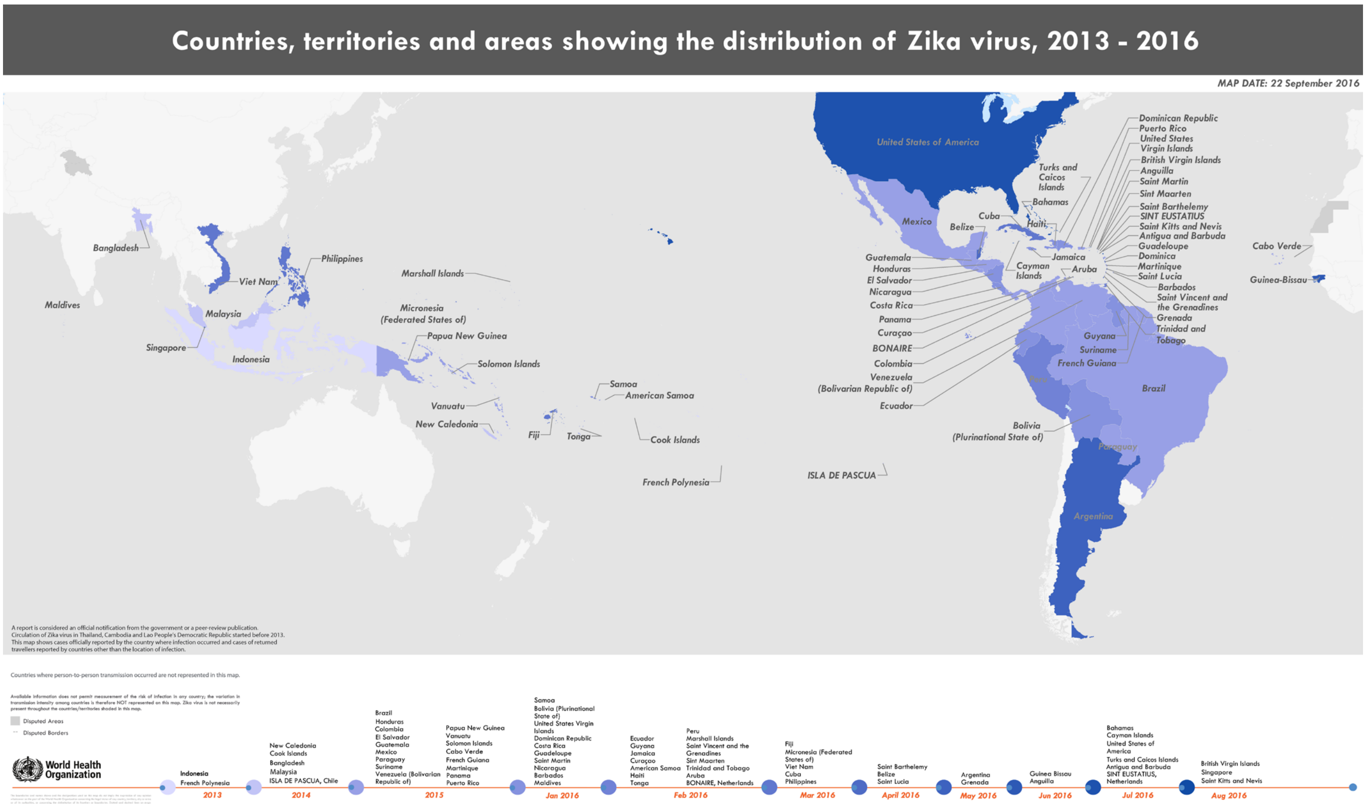
The epidemic also highlighted the need to fast-track the development of effective tests, vaccines and medicines. The final results of a trial have just been published, confirming the protective efficacy of an Ebola vaccine, which may prevent future Ebola outbreaks from having as devastating consequences (WHO, 2016b). A new WHO initiative, the blue print to accelerate Research and Development (R and D) for severe emerging diseases with no or insufficient control measures, has been established. Furthermore, the Coalition for Epidemic Preparedness Innovations has recently been established with an initial investment of EUR 431 million from the governments of Germany, Japan and Norway, and from the Bill and Melinda Gates Foundation and the Wellcome Trust in the United Kingdom. This alliance aims to finance and coordinate the development of new vaccines to prevent and contain infectious disease epidemics.

3.11.2.3 Zika

Zika is caused by a flavivirus, from the group of viruses that cause dengue, yellow fever, WNV and Japanese encephalitis. The main vectors of Zika are Aedes aegypti mosquitos, which are common in dwellings and carry other viral infections. Zika virus was first recognised as a cause of human disease in 1953, but only usually produced a mild and self-limiting illness without lasting consequence (Macnamara, 1954). However, in December 2015, reports were emerging of an epidemic of microcephaly in Brazil (ECDC, 2015a).

FIGURE 3.52

Distribution of Zika virus
Source: WHO



Microcephaly is a severe neurodevelopmental disorder caused by a failure of the brain to grow normally in the foetus, leading to an abnormally small head and impaired development (PAHO/WHO, 2015). The epidemic was confirmed to be caused by the Zika virus, which was new to Brazil (Campos et al., 2015). In addition to microcephaly, Zika causes a range of neurological and other congenital abnormalities in the developing foetus (WHO, 2016c), and severe neurological complications have also been observed in some adults and children, including Guillain-Barré Syndrome, which requires specialised intensive support (Oehler et al., 2014). Zika was declared a PHEIC under the International Health Regulations in February 2016 (WHO, 2016d).

Zika requires urgent prevention investment and control measures, which will take time to fully develop.

Zika is now spreading in the Americas to several other countries in South America, Central America and North America, and imported cases have been recorded in Europe (ECDC, 2015a, 2015b, 2016; Hennessey et al., 2016). Although in November 2016, it no longer had the status of a PHEIC, questions remain unanswered on the best means of controlling the virus and its impacts. The disease is spread by mosquitos, which are very difficult to control using conventional vector control methods (Yakob and Walker, 2016). This has required a major investment into accelerating novel vector control strategies, which will require years of intensive testing, evaluation and regulatory oversight (Daudens-Vaysse et al., 2016). Work is under way to speed up the development of vaccines, which will have to be safe for pregnant women and women of child-bearing age, effective with one dose, cheap and scalable to large volumes of production (Maurice, 2016).

The social consequences of the severe complications of Zika are formidable. The congenital abnormalities are a cause of fear and anxiety among women who are, or may become, pregnant. In some cultures, women who have children with abnormalities are isolated or stigmatised in their communities (WHO, 2016e). Family planning services may be weak, difficult to access or not culturally acceptable in some areas, and many countries do not allow abortion even for medical reasons, so the impact on affected women and their families, and the need for longer-term social provision and disability services, must be addressed (WHO, 2016f).

3.11.2.4 Human immunodeficiency virus (HIV)

Human immunodeficiency virus HIV is a type of retrovirus that is transmitted by the exchange of body fluids (breast milk, blood, semen and vaginal secretions) from infected individuals. The virus attacks and destroys infection-fighting CD4 cells of the immune system and weakens the host's defences, leading to Acquired Immune Deficiency Syndrome (AIDS). Even without treatment, there is often a long time lag (on average 10 years) between the acquisition of infection and the onset of AIDS (Poorolajal et al., 2016). Immunodeficiency increases the susceptibility of individuals to a variety of infections, many of which are not dangerous to people with strong immune systems, necessitating early diagnosis and appropriate treatment (WHO, 2016g).

Human immunodeficiency virus/acquired immune deficiency syndrome (HIV/AIDS) provides an example of the problems in managing a pandemic when early detection is poor.

HIV was first identified in 1983 and was definitively linked to AIDS patients in 1984 (Blattner et al., 1988). A reluctance to address the common transmission factors directly through effective social engagement may have impeded early efforts to limit the extension of the epidemic, which is now a pandemic. To date, approximately 75 million people have been infected with HIV and it is considered that 36 million people have died from HIV-related causes (WHO, 2016h). Despite the predominance of HIV/AIDS cases in sub-Saharan Africa, recent reports state that eight out of 12 countries in Eastern Europe and Central Asia have experienced increases in new cases of HIV infections (UNAIDS, 2016).

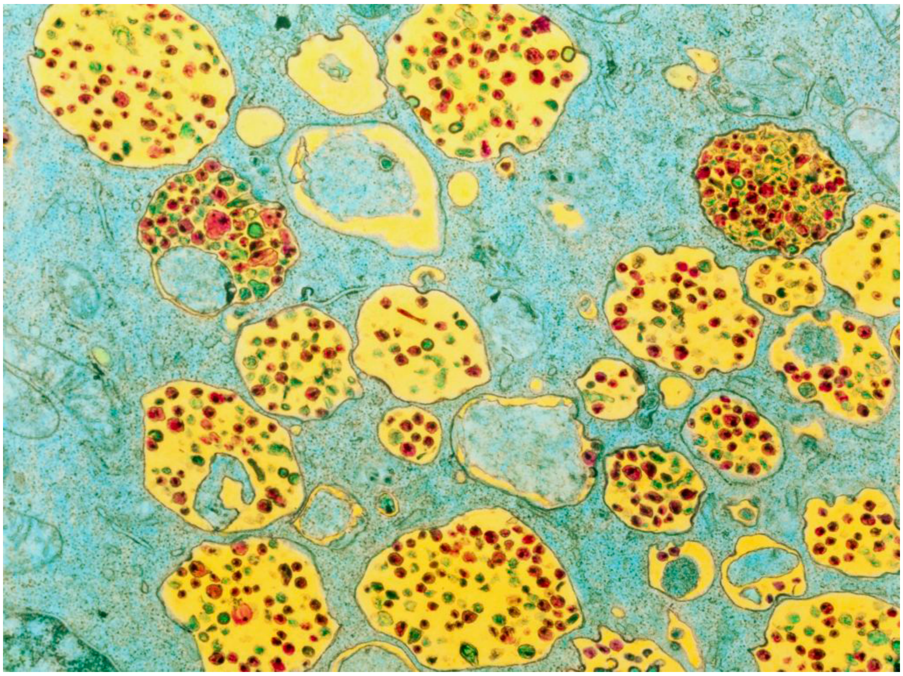
Even with extensive education programmes, the social, economic, political and environmental structural factors that increase susceptibility to HIV infection and undermine prevention and treatment efforts continue to pose challenges (Seeley et al., 2012).

HIV infection risks include men who have sex with men, unprotected sex outside a stable relationship and injecting drug use. Safe infection control practices are crucial to prevent transmission in health-care settings. Fear of stigmatisation and discrimination can prohibit access to health services (Mahajan et al., 2008). Women are also particularly vulnerable in cultures where they have little power over their sexual behaviour (Tsasis and Nirupama, 2008). Conditions correlated with safe behaviours include knowing an individual's HIV status, possessing skills for implementing safe sex, perceiving risk accurately and having peer support to build safer behaviours (Coates et al., 1988).

The economic impact of HIV is also significant. Although no definitive figures for Europe have been found, it is estimated that, on average, the epidemic causes a reduction in GDP of 2-4 percentage points across affected African countries (UNDESA, 2001). Annual HIV/AIDS mortality has reduced from 2.3 million in 2005 to 1.5 million in 2013 as a result of the introduction of highly active antiretroviral therapy (Granich et al., 2015). This effective treatment increases survival by up to 25 years following infection (Poorolajal et al., 2016). Global treatment coverage reached 46 % at the end of 2015. However, in Eastern Europe and Central Asia, only 21 % of those living with HIV are receiving treatment, owing to a lack of resources and political will (UNAIDS, 2016). Further work has been proposed by the United Nations General Assembly High-Level Meeting on Ending AIDS to terminate the AIDS epidemic by 2030. Intensified efforts are required to reach this target, including the strengthening of HIV therapy with pre-exposure prophylaxis, ensuring that people with HIV know their status, filling the treatment gap and reaching and protecting vulnerable groups such as women and children through an improved surveillance system (WHO, 2016i). Increased efforts should also be directed at strengthening human rights and combatting stigma and discrimination against people with HIV infection.

FIGURE 3.53

HIV virus
Source: PHE EDAM



3.11.3 The International Health Regulations and pandemic preparedness

Currently, there are two international mechanisms that have been created by the WHO to respond rapidly to international health emergencies: the Global Outbreak and Response Network (GOARN) and the International Health Regulations IHR (2005).

The Global Outbreak and Response Network GOARN has its secretariat in the WHO and is a worldwide partnership of agencies, institutions and networks, with expertise to support the response to epidemics wherever they may occur. Since 2000, it has coordinated over 130 international public health operations (WHO, 2015).

The International Health Regulations (2005) is an international legal instrument which is key to the Sendai Framework for DRR and its implementation and provide a comprehensive framework of definitions, principles and responsibilities that are 'designed to prevent the international spread of disease' (WHO, 2005). The IHR set out State Party obligations to develop certain minimum core public health capacities in surveillance and response at the local and national levels. Within the European Union, the European Centre for Disease Prevention and Control (ECDC) is responsible for identifying, assessing and communicating current and emerging threats to human health posed by infectious diseases. WHO Europe and the ECDC work together to develop a single European reporting and response system, and the ECDC assists EU Member States in certain aspects of IHR implementation, via Decision 1082/2013/EU.

The IHR also specify procedures for the determination by the Director-General of a PHEIC and the issuance of corresponding temporary recommendations (WHO, 2005). In the case that a potential PHEIC is notified, the IHR sets out the procedure for the establishment of an Emergency Committee of relevant experts selected by the Director General that will provide views on whether the event constitutes a PHEIC (and when it ceases to be) and on recommendations to be given on health measures to prevent or reduce the international spread of disease and avoid unnecessary interference with international traffic (WHO, 2005). During a PHEIC or any other public health event, countries may require and request assistance with the management of the epidemic. However, the overall capacity to control and prevent the occurrence of epidemics or a pandemic is only as good as the weakest link in the chain and, similarly, the effectiveness of an international alert system will only be as good as its implementation.

The 2009 H1N1 flu virus pandemic marked the first use of the IHR 2005 to address a global public health emergency (Katz and Fischer, 2010). Although this pandemic saw significantly fewer fatalities than the 1918 'Spanish flu' pandemic (Morens and Fauci, 2007), it still resulted in significant pressures on responding organisations (particularly health systems), coordinating governments and the public (Girard et al., 2009).

Pandemic influenza differs from the more routine epidemics of seasonal influenza that populations face on a regular basis in a number of ways:

- a pandemic is, by definition, a global epidemic, affecting all countries across the world at the same time (Cox et al., 2003);
- a pandemic can occur at any time of the year, unlike the more predictable seasonal epidemics (Lipsitch et al., 2009);
- most of the population will be susceptible to the pandemic influenza virus owing to the novelty of the virus compared with previous circulating strains, rather than the typical at-risk groups of those at extremes of age or with known clinical risk factors (Cox et al., 2003);
- a pandemic could occur in multiple waves (Ngyuen-Van-Tam and Penttinen, 2016).

The International Health Regulations specify the core capacity requirements of countries to prevent the international spread of disease, one of which is preparedness. The challenges with preparedness planning for a pandemic are manifold and reflect the uncertainties in how such an event could manifest, as well as the potential impact.

Pandemic preparedness varies across states and is influenced by many underlying factors. These include the resources available to plan for and respond to something as unknowable as a pandemic, where limited resources are understandably targeted towards known immediate challenges such as childhood immunisations, HIV/AIDS or clean water (Nicoll et al., 2016; Oshitaniet al., 2008). Even if a country is developing robust pandemic preparedness arrangements, ad hoc or unexpected events can cause activity to be derailed, postponed or abandoned, such as an outbreak of another disease or a major natural disaster (Campigotto and Mubareka, 2015; CCDM, 2008).

Pandemic preparedness and response goes much wider than health-care systems. While the link with social care is easily recognised, maintaining the business continuity of other essential services (such as emergency services, schools, fuel, power, education, prisons, etc.) is necessary to mitigate any further unintended or unanticipated impacts on the health response. On account of the need for cross-sectoral involvement, and the potential broad disruption that a severe pandemic might generate, pandemic planning may be considered a model for large-scale disaster planning.

While all sectors of society are involved in pandemic preparedness and response, the national government is the natural leader for overall coordination and communication efforts. Public perceptions of the state can therefore influence the success of the response; during the 2009 H1N1 pandemic, health authorities were viewed as trustworthy in the United Kingdom, while in Spain, there was public speculation that the vaccine was driven by the economic interests of the pharmaceutical industry, which led to poor vaccine uptake (Henrich and Holmes, 2011; Prieto et al., 2012).

As in all disaster preparedness scenarios, there are a number of key essential elements that underpin robust pandemic planning (CCDM, 2008; Fineberg, 2014; WHO, 2009):

- having national, subnational and local strategic, tactical and operational plans;
- working across multi-agency partnerships, including the private and voluntary sector organisations;
- planning for a risk-based and flexible response;
- testing and exercising plans, and ensuring that staff are appropriately trained;
- using routine surveillance to ensure early warning of pandemic arrival in the country;
- ensuring that communication routes are effective for a range of audiences (including the public, health-care workers and politicians);
- providing access to effective and appropriate clinical counter measures;
- providing access to appropriate personal protective equipment for health-care workers;
- ensuring that essential services and business have considered their business continuity arrangements;
- planning for special groups and settings (such as the justice setting, migrants and persons in transit, and hard-to-reach populations);
- planning to cooperate with international partners, and how to manage any border issues;
- planning for recovery.

Responding to a severe influenza pandemic is potentially one of the biggest challenges for the health sector, as well as wider society. Even if a severe pandemic never occurs, all the planning and discussion around some of the potential issues can help to inform responses to other incidents.

3.11.4 Innovative approaches for early warning and surveillance

As advances in technology and communications have increased the opportunities for international travel and trade, both of which are recognised drivers of the emergence and re-emergence of human pathogens (Suk et al., 2008), so have they increased the opportunities for surveillance to enable the rapid detection and assessment of threats, and the sharing of intelligence across international borders. Key advances that have improved surveillance capacities include:

- increases in computing power and storage capacity, enabling the rapid analysis of large disease incidence datasets;
- developments in electronic communications systems and information standards enabling machine-to-machine data transfer and rapid sharing of information, nationally and internationally (Guglielmetti et al., 2005);
- internet-based search and retrieval applications that scan for media and other informal reports that might indicate the emergence of an infectious disease epidemic (Keller et al., 2009; Anema et al., 2016);
- Geographic Information Systems (GISs) that enable the analysis and display of information that can assist in identifying clusters or assessing environmental determinants of exposure (Freifeld et al., 2008).

Infectious disease modelling that integrates data on environmental variables with health and disease data may also help to anticipate future disease threats, thereby providing support tools for decision-makers (Suk et al., 2014; Semenza et al., 2013). The emergence of the field of digital epidemiology, which is the science of conducting epidemiological studies using data from digital tools and data sources from the internet such as social media, is already having an immediate impact on the operational activities of public health agencies worldwide (Salathe et al., 2012). There are, however, considerable challenges, such as filtering large volumes of unstructured data, and ethical issues around data-sharing and use (Brownstein et al., 2008).

Informal sources for event-based surveillance can provide very early signals of significant health events, sometimes before they are detected through official indicator-based channels.

An important innovation in the 2005 revision of the IHR was to change the focus of the regulations from one limited to specific diseases to one applicable to health risks, irrespective of their origin or source (WHO, 2005). This has a number of key benefits in terms of the early detection of epidemic threats, including not only the broadening of the scope of infections (and other potential causes of PHEICs) covered, but also removing a dependency on awaiting definitive (laboratory) confirmation of the aetiology of a detected case or incident of potential international concern before reporting. As a consequence, monitoring of the evolution of diseases and factors affecting their emergence and transmission can occur at an earlier stage than in the past.

3.11.5 Conclusions and key messages

Epidemics and pandemics are types of disasters that are capable of overwhelming health systems, disrupting communities and challenging political leadership, and that often have devastating societal, economic and psychological impacts. Infectious diseases can behave unpredictably and have a capacity to evolve and adapt to exploit population susceptibilities, thus posing a perpetual challenge in the context of DRR and DRM.

The recommendations below have been structured according to the pillars of the DRMKC, namely partnership, knowledge and innovation. The DRKMC has been developed in order to support the translation of complex scientific data and analyses into usable information, providing science-based advice for DRM policies, as well as timely and reliable scientific-based analyses for emergency preparedness and coordinated response activities.

Partnership

Multidisciplinary working is essential in order to reduce the impacts of epidemics and pandemics. Information-sharing between sectors (e.g. animal health, veterinary, transport, environmental health, food, water and sanitation) is key to preventing the spread of infection and assessing evolving risk through surveillance, particularly as many emerging infections are zoonoses and may first manifest in livestock. As infectious diseases do not respect borders, strong collaboration and coordination between national and international structures is fundamental to limiting morbidity, mortality and societal disruption. Comprehensive preparedness planning involving multi-agency partnerships can also make the transition from disaster to recovery more effective.

Knowledge

Control measures should be evidenced-based when possible, and preparedness plans should be clear, flexible and regularly tested in order to provide a timely, appropriate and effective response. Countries should also be supported to comply with the International Health Regulations which set out the core competencies that countries should have with respect to their national surveillance and response, and their obligation to report events that constitute a PHEIC.

Innovation

Syndromic surveillance and the use of innovative methods to collect event-based data, for example through the internet, may assist in the early detection of disease outbreaks. In the absence of existing effective treatment or preventive measures, investment is required into research to develop new preventive and/or therapeutic strategies; two recent examples of this are the WHO blue print for accelerating Research and Development and the evaluation of an effective vaccine against Ebola, and the formation of the Coalition for Epidemic Preparedness Innovations.

Recommendations

A set of recommendations relating to the hazards has been identified and is based on the three pillars of the DRMKC:

Partnership

Recommendation 1: multidisciplinary working and information-sharing is essential to reduce the impacts of these hazards. Collaboration and partnerships are necessary both between institutions and disciplines, and need to occur at the local, national and international levels. For example, with respect to institutions and disciplines, improvements in the forecasts of storms will in part be driven by the interaction between fundamental atmosphere and ocean science with operational forecasting, so continued collaboration between forecasting centres and universities and research centres is of key importance. Between the local and national levels, a systematic approach across all sectors involving state, private, voluntary and community actors is required to understand the wider societal impacts of temperature extremes. In relation to international alerting and response, countries are now legally bound by the International Health Regulations to report on potential transboundary risks of hazards such as infectious diseases, allowing the determination (if required) of a PHEIC. This has led to the overarching implementation across government and all sectors of the Sendai framework.

Knowledge

Recommendation 2: it is recommended that an enhanced understanding of the origin, behaviour and evolution of these hazards to facilitate local, national and regional risk assessment is needed. This is consistent with priority one of the Sendai framework, which states:

Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be leveraged for the purpose of pre-disaster risk assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters.

For instance, climate change is predicted to exacerbate the frequency and severity of droughts; therefore, observed and projected trends in drought hazard need to be understood and considered in management plans.

Recommendation 3: the generation of knowledge and evidence to address research gaps around risk will enable a shift towards a more pro-active approach as opposed to the prevailing reactive approach. The influence of different socioeconomic and cultural contexts on risk and response should also be studied. With respect to wildfires, although there is a vast knowledge of wildfire risk, information varies according to the scale at which risk is assessed and differs from local to regional or global scales. There is also a need to use standardised event documentation to enhance risk assessment where feasible.

Recommendation 4: EWSs often entail the collection, integration and analysis of different types of data, and so it is recommended to improve the interoperability of systems and exchange of data. Challenges to drought monitoring are the continuous availability of indicators covering the various hydro-meteorological components and their combined analysis into usable information for decision-making. In the context of storms, a greater understanding of how to interpret, use and communicate probabilistic forecasts is required.

Recommendation 5: preparedness plans should be clear, flexible and regularly tested in order to provide a timely, appropriate and effective response. Comprehensive preparedness planning involving multi-agency partnerships can also make the transition from disaster to recovery more effective. Managing temperature extremes can be approached from a number of perspectives, including using forecasting technology, the development of heat and cold plans, and urban design and town planning. The key essential elements that underpin robust epidemic and pandemic planning provide a useful example.

Recommendation 6: of critical importance is building knowledge on how to strengthen community resilience to hazards. For example, enhancing drought resilience in regions with high population vulnerability and low adaptive capacity should be reflected in relief aid programming, and knowledge of epidemics and pandemics should be used where possible to facilitate support and to implement population immunisation with relevant strains of vaccines.

Innovation

Recommendation 7: investment in research is needed in order for innovation to continue. For all the discussed hazards, new technologies are emerging that better assess their risk. Disasters can also act as a catalyst for innovation. The West African Ebola outbreak highlighted the need to fast-track the development of effective tests, vaccines and medicines. The final results of the targeted trial for the population at risk have just been published and confirm the protective efficacy of an Ebola vaccine, which may prevent future Ebola outbreaks from having such devastating consequences.

Recommendation 8: the internet revolution has significantly contributed to innovation; for example, syndromic surveillance to collect event-based data through social media, for instance, may assist in the early detection of disease outbreaks. The ability to draw on multiple sources of information from data networks, as encapsulated by the concept of ‘the internet of things’, also offers considerable potential for managing disaster risk related to temperature extremes

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3.7 Meteorological risk: extratropical storms, tropical cyclones

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3.9 Climatological risk: droughts

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Chapter 3

Understanding disaster risk: hazard related risk issues

SECTION IV
Technological risk

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3 Understanding disaster risk: hazard related risk issues

Section IV. Technological risk

CONTENTS

Introduction

The risk of technological accidents from man-made and natural hazards is increasing as a result of industrialisation, population growth that leads to more urbanisation and community encroachment on natural-hazard areas, and climate change. The last few years have seen major technological accidents, with significant social, environmental and economic impacts that have had repercussions around the globe. Examples include the explosions at chemicals warehouses at Tianjin Port in 2015, the Fukushima nuclear disaster caused by the 2011 Great East Japan earthquake and tsunami, and the Deep Water Horizon oil spill in 2010.

There is no overarching framework for the reduction of technological risks, and disaster risk reduction initiatives have not commonly addressed this type of risk. With the Sendai Framework for Action, the importance of technological hazards has been recognised and an all-hazards approach to disaster risk reduction is promoted. This includes dangerous situations arising from man-made activities caused by human and organisational error, mechanical failure and natural hazards — so-called Natech risk. Prevention and preparedness for these risks, and for environmental emergencies in general, also has implications for sustainable development.

There are many hazardous industrial activities that provide society with important goods and services (e.g. chemical processing, oil and gas transport and some forms of electricity production). For the purpose of this report, three examples of major technological hazards were selected and the state of play in the management of the associated risks is discussed: (1) chemical accident risks due to the relatively frequent occurrence of accidents, (2) nuclear risks due to the potential for major cross-border consequences, and (3) Natech risks as an example of a multihazard cascading risk.

3.12 Technological risk: chemical releases

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3.12.1 Introduction

In 1921, an explosion of 4 500 tonnes of ammonium nitrate sulphate fertiliser at a BASF site in Oppau, Germany, killed more than 500 people and caused considerable damage to the site and surrounding community. At the time, Carl Bosch, BASF's Nobel Prize-winning engineer said, 'The disaster was caused neither by carelessness nor human failure. Unknown natural factors that we are still unable to explain today have made a mockery of all our efforts. The very substance intended to provide food and life to millions of our countrymen and which we have produced and supplied for years has suddenly become a cruel enemy for reasons we are as yet unable to fathom.' This statement was no doubt true in 1921, when chemical manufacturing was still a new and growing industry. 100 years later, however, thanks to the work of generations of dedicated scientists in industry and academia, 'unknown natural factors' are rarely an underlying cause or chemical accidents today.

Accident reports, investigation results and media reports of recent times give overwhelming evidence that chemical accidents today are mainly caused by a failure to apply what is already known, the 'known knowns'. Improvements in our understanding of chemical accident risks and chemical accident control technologies and systems have not necessarily led directly to advances in a significant reduction in chemical accident disasters. Indeed, according to a famous study by H. W. Heinrich (1931), 98 % of all industrial accidents are preventable. However, technological disasters are by their nature '(hu)manmade' and it can be argued that a reduction in chemical disaster risk is particularly affected by the dependence on humans to manage and use the technology appropriately. Turner and Pidgeon (1997) argue that disasters arise from an absence of knowledge at some point. They occur because we do not understand enough about those forces (i.e. in industrial processes) that we are trying to harness, and, as a result, energy is released at the wrong time or in the wrong place. They are also clear that this is not just an engineering issue and that many disasters arise from social or administrative causes or the combination of technical and administrative causes.

Improvements in our understanding of chemical accident risks and chemical accident control technologies and systems have not necessarily led directly to advances in a significant reduction in chemical accident disasters.

The science of reducing chemical accident risks is now focused on the underlying causes of human failure to control the risks. Characterising causality in this way adds new dimensions to the study of chemical accident risks. In attributing causality to control, there is a recognition that further progress in reducing chemical accident risks requires strong involvement of the social sciences. Certainly, there is considerable room to examine new engineering solutions, such as the use of artificial intelligence and adapting existing control technologies to new processes. However, these types of solution are industry and even process specific and do not apply to many sectors in which accidents frequently occur. Indeed, the oil and gas industry is one of the world's oldest industries and has been the subject of massive technological investment over many decades; however, globally it is by far the leader in terms of the frequency of severe chemical accidents.

The term 'hazardous industries' comprises numerous substances, processes and equipment, with considerable variation within each category in regard to properties, function and behaviour under different conditions. Petroleum refineries, bulk chemical production (e.g. chlorine and ammonia), the manufacture of specialty chemicals (e.g. paints, dyes, plastics and resins) and pharmaceuticals are examples of industries that comprise a wide range of processes, each with their own unique risk profile and associated risk management implications. While there is less variety, there is still considerable danger in processes involving hazardous substances in the 'non-chemical' industries, such as water and waste treatment, electroplating and food production. In addition, distribution activities, including transport by rail, road and pipeline, as well as explorative and extractive activities both on- and offshore, also are important sources of chemical accident risk. The evaluation of the potential for chemical accidents triggered by natural hazards (so-called Natech accidents, see Chapter 3.14) or other external events, as well as incidents caused by intentional acts, involves additional factors (e.g. natural hazard forecasting, earthquake protection, site security, etc.). These types of incident risks are not specifically addressed in this paper, but it is assumed that standard risk management practices, as here, also help to prevent and mitigate such events.

In societies with mature risk regulation, such production and use of hazardous substances is permitted provided that the risks remain at a level deemed acceptable by the local community and society in general. This paper presents evidence that industrialised countries are still far from achieving an acceptable level of chemical accident risk. It then describes a number of underlying causes common to all industries and societies that are impeding progress in chemical accident risk reduction.

3.12.2 Chemical accidents with serious impacts continue to occur with disturbing regularity

Chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk-reduction efforts. Media monitoring over the last several years shows consistently that at least 25-30 chemical accidents with worker or community impacts are reported each month around the world in industrialised countries. Preliminary results of a study by Wood et al. (2016) of accident reports covering all major chemical hazards in fixed facilities and transport over the last 5 years (2012-16) identify 29 national and regional chemical accident disasters and 21 chemical accidents with evident high local impact.

Chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk-reduction efforts.

Disasters were classified on the basis of reported impacts on human health, the local community or the environment or on the basis of significant attention at a national level in processing and storage facilities and distribution networks (transport and pipelines). 'Local shocks' were are accidents identified on the basis of important local impacts as reported in the newspapers, corresponding to at least gravity level 3 on the European Gravity Scale for Industrial Accidents (Committee of Competent Authorities for Implementation of the Seveso Directive, 1994). In total, these accidents accounted for

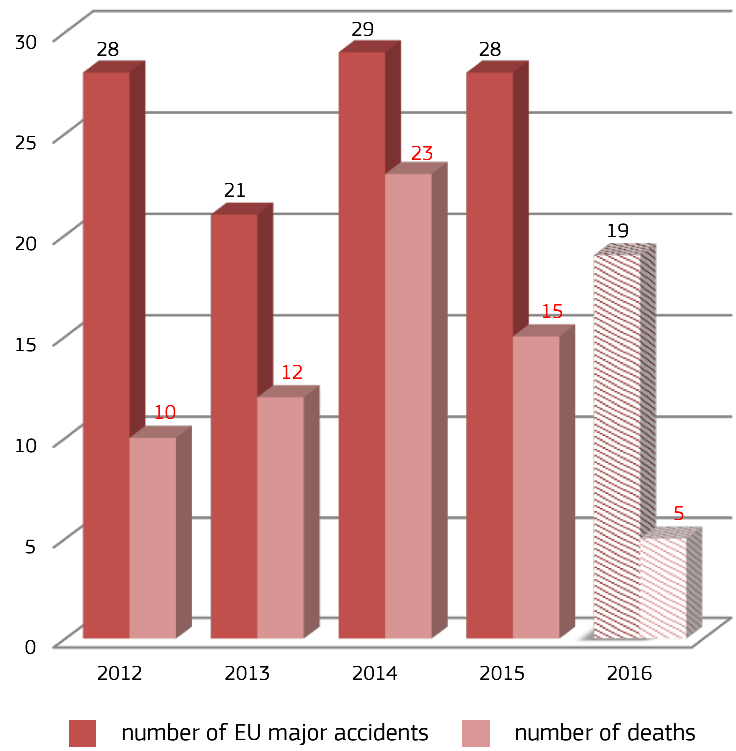
928 deaths, and (where reported) 22 973 injuries. In addition, significant environmental impacts were recorded, with one pipeline disaster reaching USD 257 million (EUR 236 million) in restoration costs (LATimes, 2017). More than 7 000 people were evacuated for several months owing to a slow leak of natural gas that was finally sealed off in February 2016 (October 2015-February 2016, Aliso Canyon, CA, USA). Insurance companies recorded nine accidents resulting in >USD 100 million (EUR 92 million) in damages, including two accidents (Hazardous goods warehouse, Tianjin, China, 12 August 2015 and petroleum refinery fire, 15 June 2014, Achinsk, Russia) costing >USD 1 billion (EUR 0.92 billion). Many other impacts, including job losses, environmental impacts, emergency response costs, damage to nearby buildings and market and production losses were sparsely reported, but businesses in West Virginia were reported to have lost USD 61 000 000 (EUR 56 000 000) in 4 days.

Belke (1998) states:

'From the perspective of the individual facility manager, catastrophic events are so rare that they may appear to be essentially impossible, and the circumstances and causes of an accident at a distant facility in a different industry sector may seem irrelevant. However, from our nationwide perspective at [U.S.] EPA and OSHA, while chemical accidents are not routine, they are a monthly or even weekly occurrence, and there is much to learn from the story behind each accident.'

FIGURE 3.54

European Commission eMARS reporting system.
Source: eMARS (2012)



The frequency of severe chemical accidents is at odds with society's expectations. Societies are becoming increasingly risk averse and failure is less readily tolerated. There are indications that the frequency of serious chemical accidents is higher than expected in many industrialised countries. In 2015 the number of deaths from major accidents on the ≈10 000 EU Seveso sites was estimated to be at least 15 (see Figure 3.54). This statistic, if confirmed, means that the frequency of one fatality on a major hazard site in the European Union was around 1.5×10^{-3}, that is, above acceptable limits for individual risk in EU Member States that use quantitative criteria. (e.g. the criteria established for individual risk (probability of 1 fatality) is $< 1 \times 10^{-6}$ in both the Netherlands and the United Kingdom, although lower probabilities may be accepted in some circumstances, for example, depending on economic costs and benefits (Ham et al., 2006)). In 2013, the President of the United States issued an Executive Order to improve chemical facility safety and security following various high-profile chemical accidents. In recent years, chemical accident frequency and severity in other major industrialised countries, such as China and Brazil, has been approaching, or has approached, levels that would be generally considered unacceptable in an industrialised economy.

Globalisation and the export of technology have increased chemical accident risk outside the EU.

Similar trends are noted in developing countries (see Figure 3.55). The terms 'developed' and 'developing' are used in this paper to differentiate countries with modern physical and institutional infrastructures from those that are still in the process of establishing such infrastructures. 'Industrialised countries' refers to both developed countries and newly industrialised countries, in which the manufacturing sector has a significant economic presence. China enacted the Emergency Event Response Law of 2007 as a result of an important lesson learned from two major chemical accidents in China: the 2003 gas well blowout in Chongqing that caused 243 deaths mainly from hydrogen sulphide inhalation, and the 2005 release of toxic substances into the Songhua River (Zhao et al., 2014). New legislation in Brazil covering chemical risks stems from broad-based concerns about problems connected with chemical safety that have grown in intensity and extent in the last two decades. Many developing 2014countries have experienced rapid growth in hazardous operations in particular segments of the oil and gas, chemical and petrochemical industries and mining, driven by a combination of factors, including increased demand in emerging economies, access to raw materials and the need to lower production costs, facilitated by a decline in trade barriers and government incentives to attract foreign investors (de Freitas et al., 2001).

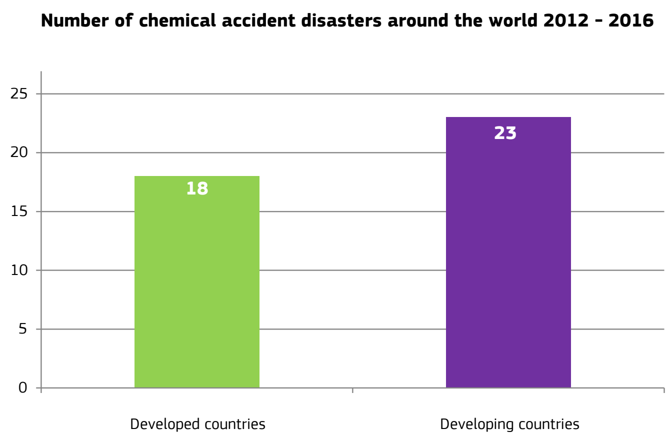
FIGURE 3.55

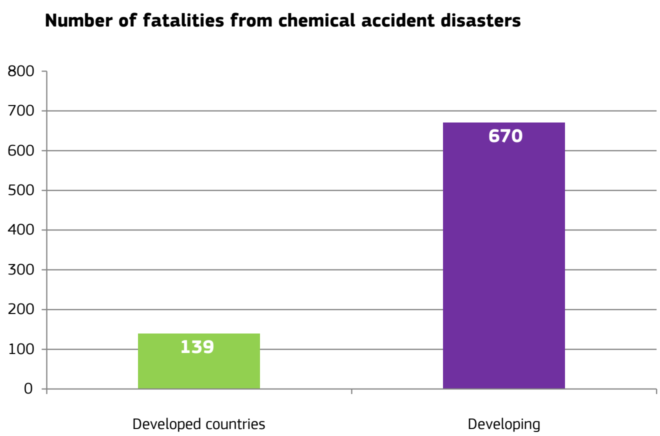
Chemical accident disasters reported from 2012-16 (N=29), occurring in industries producing, handling or storing dangerous substances, including oil and gas, petrochemical and chemical industries, as well as 'non-chemicals' business, such as power generation, food manufacturing and water treatment.

The frequency of chemical disasters occurring in developing countries in the period 2012-16 was more or less equivalent to that of developed countries, but fatality rates were much higher. It is speculated that risks to humans are less well-managed in developing countries.

Non-human impacts (environment, economic loss, property damage) were often quite severe in both developed and developing regions.

Source: Wood et al. (2016)





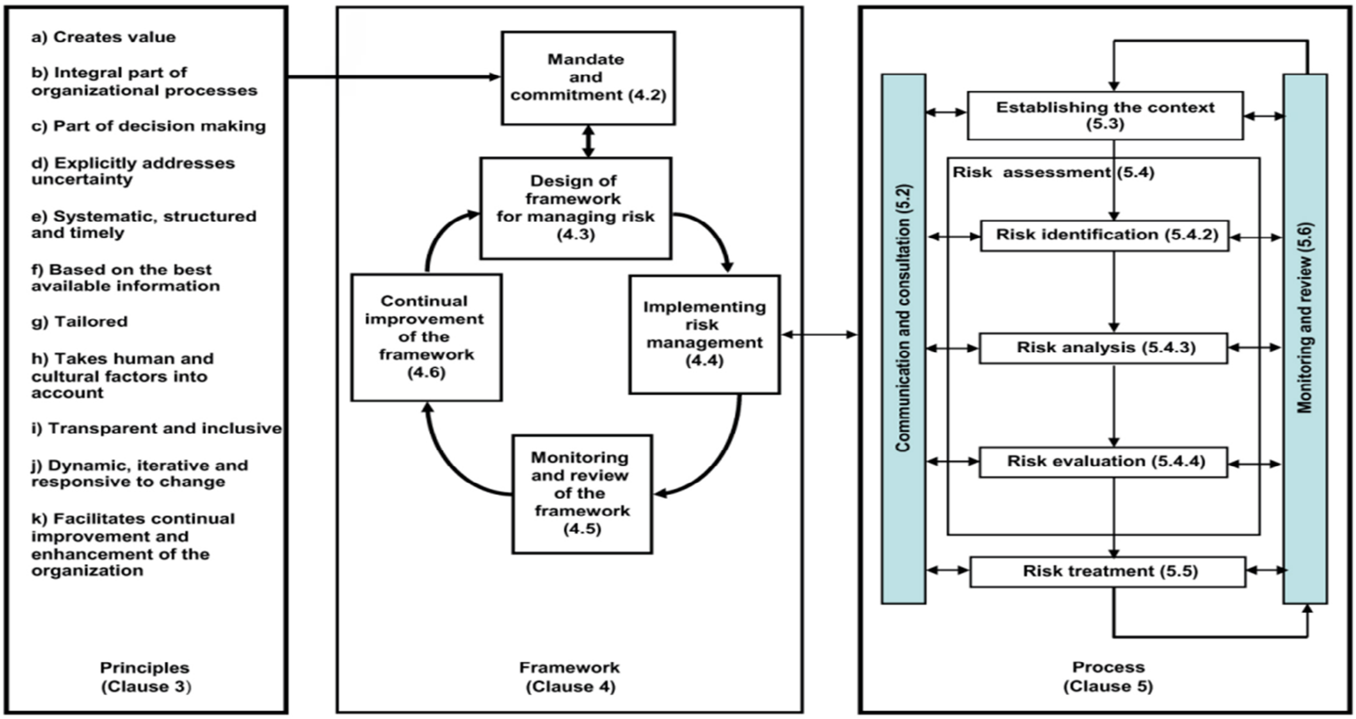
3.12.3 Chemical risk management in modern times: the theory is well-established but implementation lags behind

There is currently considerable agreement on the fundamental principles of process safety management which, if understood and properly applied, would prevent a large majority of chemical accidents that still occur today. These essential principles are then applied in the context of an ISO 31000:2009 risk management process (see Figure 3.56). From an operational perspective, successful risk management comes from applying layers of protection throughout the process life cycle (design to decommissioning), starting with the reduction of the hazard itself, and working outwards to accident prevention, mitigation and response. Above all, it is the organisations and individuals that manage all of these elements. For this reason, hazardous sites are expected to have a safety management system in place, a derivative of the well-known 'management system' concept, to manage the interface of humans with hazardous processes in order to minimise process hazard risks.

The hazardous industries understand in principle how to manage chemical accident risks. Why, then, do these industries continue to repeat failures of the past and have accidents and, sometimes, disasters? A study of accidents of the past few decades and the work of numerous experts on man-made disasters, including chemical accidents, as well as nuclear, space and aviation disasters, suggest that the causes are systemic. Sweeping changes in business philosophy and the explosion of opportunity created by new technology, such as the increasing reliance on the computerisation of business processes, have brought ben-

FIGURE 3.56

Relationship between the risk management principles, framework and processes (ISO 31000:2009 Risk management – Principles and guidelines)
Source: International Organization for Standardization (n.d.)



efits as well as a share of risks. These risks are particularly notable for man-made risks where small changes to complex systems can unwittingly remove barriers to initiation or propagation of a potential hazard event.

It is a fact that technological disasters, past and present, not just chemical disasters, have relevant and timeless lessons for risk managers in all industries, many of which have been recently documented by Gil and Atherton (2008, 2010)). A number of high-profile technological disasters occurring since 2000 have challenged some experienced risk management experts to identify the patterns underlying the repeated failures behind the latest round of technological accidents, building on the work of Perrow (1984) and Rasmussen (1975), among others, on managing risk in complex systems, by means of new approaches. Hollnagel et al. (2008) have introduced the concept of 'resilience engineering' for technologically complex industries. They look at risk management from the organisational perspective of the large multinational and government operators that are the owners and operators of these technologies. In resilient systems, individuals and organisations habitually adjust their performance to match the variability of risk over time, 'prior to or following changes and disturbances so that it can continue its functioning after a disruption or a major mishap, and in the presence of continuous stresses.' Klinke and Renn (2006) suggest that 'risks must be considered as heterogeneous phenomena that preclude standardised evaluation and handling' in their paper describing governments' potential role in managing systemic risks. Le Coze (2013) proposes that new analytical models for safety assessment take into account the dynamic and systemic aspects of safety.

Chemical accidents nowadays are often derived from the failure of industry, government and society to understand the profound effect that their choices have on risk.

Kletz (1993) commented on the pattern of corporate memory loss in United Kingdom companies as far back as 1993. More recently, Baybutt's 2016 review of accidents investigated by the U.S. Chemical Safety Board since 1998 concluded 'Remarkably, all of the reviewed incidents involved some type of deficiency or omission in adhering to established process safety practices. In many cases there were multiple deficiencies and omissions.' Wood et al. (2016) also found that where probable causes of accidents have been ascertained, they are most often associated with predictable circumstances in which control measures were insufficient as a result of poor risk management or, in some cases, a lack of adequate awareness of the risks. This finding is further substantiated in various 'lessons learned' publications, such as the MAHB Lessons Learned Bulletin, where analyses of recent and older accidents are side-by-side, identifying often remarkably similar findings about what went wrong (European Commission Joint Research Centre, 2012-2016).

The research of Taylor et al. (2016) collated and synthesised circumstances and causality associated with 12 significant technological accidents, of which five were chemical accidents, and identified numerous organisational failures associated with leadership, oversight and scrutiny, and communication that were common precursors to the events studied. Their study identified a number of factors, including the general decline of safety departments, oversimplification to upper management through aggregation of indicators and other inputs, poor understanding of operational 'reality', lack of processes and systems that ensure that process safety risks are properly assessed, and the influence of commercial interests, as among the key forces that shaped the events leading to the accidents. Arstad and Aven (2017) point out that 'it is dangerous to assume that system boundaries can be limited to the sharp end of the business … wide and open system boundaries recognise the importance of many more risk sources and safety.' They also remark on the tendency to oversimplify risks ('complexity is incompressible') associated with complex technologies. With petroleum-based industries as a primary candidate, Carnes (2011) outlines a High Reliability Governance model based on multiple engagements between government and industry actors, which continually reinforces common performance expectations and a high-level safety culture.

A large number of scientific studies of technological disasters focus on big, well-resourced organisations. However, it is a fact that many serious accidents around the world originate in small and medium-sized enterprises

(SMEs) that are operating fairly simple processes (e.g. warehouses, fuel distribution) (European Commission Joint Research Centre, 2012-2016; Gil and Atherton, 2010; Howard, 2013; State Administration of Work Safety (China), 2016; U.S. Chemical Safety Board, 2016b). While they are not all 'disasters', the United Nations Development Programme (UNDP)'s 2004 report on reducing disaster risks correctly cites that accidents with local impacts are an important part of understanding the scale and dimensions of particular threats. In addition, there is some evidence that government and society unwittingly, for sometimes for very good reasons, accept more risk in relation to SMEs. These companies often present significant challenges for regulators because they lack adequate expertise or even sufficient hazard awareness to manage their risks within acceptable limits. Typical cases of this type are the small fireworks manufacturers whose premises have been the sites of several accidents with multiple fatalities in the past 5 years within the EU (eMARS, 2012; Wood et al., 2016). Moreover, recent tragedies, such as the disasters of Tianjin, China (2015) (State Administration of Work Safety (China), 2016) and West, Texas (2013) (U.S. Chemical Safety Board, 2016b) indicate that, in these cases, even though the presence of a significant hazard was known, the government failed at many levels to ensure that adequate prevention, mitigation and preparedness measures were in place.

Twelve underlying causes are cited as challenges to controlling chemical accident disaster risk in current times.

The authors of this paper have identified 12 types of underlying causes of chemical accidents based on their own studies of accidents and research of other experts. They are based in part on causal typologies developed by the various experts in man-made risks already cited in this paper. They also reflect the authors' extensive experience in studying and investigating the causes of chemical accidents, bringing in the small business and governmental

BOX 3.3

Distant leadership and optimisation strategies: a recipe for organisational failure.

The accident at a multinational liquefied natural gas plant in South Gippsford, Australia, in 1998, known as the 'Longford accident', is attributed in part to a series of company misjudgements, including relocation of expertise to another site, poor intercompany communication and the insufficient prioritisation of safety over profits . Two people were killed and eight were injured. The state of Victoria was left without its primary gas supply, crippling industry, in particular commercial industry, with an estimated economic loss of at around AUD 1.3 billion (Hopkins, 2014). Similarly, the lack of adequate oversight of operations at a fuel storage terminal, coupled with poor intercompany communication exchange, was considered a leading cause of the devastating Buncefield explosion and fire at the Buncefield fuel terminal, Hemel Hempstead, United Kingdom, in 2005 (U.K Health and Safety Executive, Environment Agency and the Scottish Environmental Protection Agency, 2005). The primary causes were the failure of two-level instruments on the tank that overflowed. The alarm and overfill protection functions did not operate as a result. The analysis of the event indicates that it was the result of a sequence of management failures in addressing known risks and performance uncertainties over a period of months and even years prior to the incident (Howard, 2013).

dimensions that are sometimes not well covered in research.

Causes are not necessarily mutually exclusive, since the presence of one underlying cause can make a site susceptible to other dangerous mentalities and conditions. The 12 underlying causes are as follows:

1. **Lack of visibility.** A paucity of chemical accident data and inconsistent media attention has exacerbated the lack of interest in reducing chemical accident risks in recent decades. The limited public databases on chemical accidents leave society without any performance measures. With the exception of high-cost accidents reported by insurance companies, there are no published statistics on accident frequency. International media picks up only high-profile disasters, which form only a small fraction of the chemical accidents that happen every week. Moreover, as noted by Quarantelli (1997), there is also a misleading tendency to equate disastrous occasions only with casualties and property damage. Hence, there is far less visibility for chemical accidents that cause significant social disruption, such as evacuation, loss of drinking water, severe environmental damage, job loss and elevated and often uncertain exposure to health risks.

2. **Failure to manage risk across boundaries.** The organisations and individuals in charge of chemical accident risks usually define challenges in terms of their own expertise and jurisdictions. There are numerous incidents in the EU eMARS database indicating a failure to communicate information to those who need it, both internally to organisations and externally to other industrial sectors, professional disciplines and international boundaries (eMARS, 2012; European Commission Joint Research Centre, 2012-2016). Chemicals risk management in industry has traditionally been assigned to chemical and mechanical engineers who have little training in human and organisational factors. Government assigns monitoring and enforcement on the basis of who is affected, that is, on-site workers (labour authorities), off-site communities (civil protection authorities) or the environment (environmental authorities). The large multinational industries, such as oil and gas, and chemical manufacturing companies, exchange little information on chemicals risk management with other (and often less-resourced) industrial sectors, such as pyrotechnics production, pharmaceuticals and various non-chemical businesses. Similarly, government oversight and enforcement tends to follow jurisdictional boundaries in the geographic sense. This limitation can lead to

BOX 3.4

When industry and government both fail to learn lessons from past accidents.

Even major disasters are ignored and forgotten. A case in point is the massive explosion involving ammonium nitrate fertilisers that occurred in West, Texas, USA in 2013, which killed 15 people and destroyed 140 nearby homes. This incident was preceded by some well-known disastrous explosions involving ammonium nitrate fertilisers, in particular, Oppau, Germany, 1921 (>500 deaths); Texas City (Texas), USA, 1947 (581 deaths, > 3 000 injuries); and Toulouse, France, 2001 (29 deaths, > 2 500 injuries).

It appears that lessons from prior accidents about handling ammonium nitrate fertilisers had not been taken into account in either industry practices or fire protection laws (BP Refineries Independent Safety Review Panel, 2007). Furthermore, the potential off-site consequences of an ammonium nitrate explosion were ignored by the prevailing environmental regulation that had jurisdiction only over substances with toxic release potential. Emergency and land-use planning measures prior to the accident did not have any special provisions for a school, nursing home or residences in close proximity (U.S. Chemical Safety Board, 2016b).

a lack of regional coordination on chemical accident risk management and may present serious transboundary accident risks. The failure to see beyond one's own boundaries fosters a piecemeal approach to risk management and results in lost opportunities in sharing lessons learned and developing common strategies.

3. **Failure to learn lessons from past accidents and near misses.** There is substantial evidence that neither governments nor public authorities have learned sufficiently from past accidents. Taylor et al. (2015) note that that failure to learn was recurrent in organisations involved in some of the significant man-made disasters of the last 30 years in Europe and elsewhere. According to the study, barriers to learning were related to culture, the poor communication of findings and 'lost' corporate memory, a failure to investigate prior events, a narrow view of what was useful to learn and what constituted an opportunity to learn, and the silo effect, such that information on events does not cross internal organisational boundaries. An effective risk management programme incorporates the systematic study of past accidents occurring both on-site and elsewhere. Learning from one's own accidents (in one's organisation or jurisdiction) is important to diagnose specific weaknesses and trends. Learning from relevant accidents that occur on other sites and in other locations is essential to map all possible pathways that could lead to an accident. Even when problems are recognised, the failure to learn leads to inappropriate solutions. In industry there is a tendency to respond with increasing complexity, in the form of new, but not necessarily better, technology. Similarly, governments will respond with new or stricter, but not necessarily better, regulation.

4. **Social drivers, including economic trends.** Avoiding situations in which judgement is clouded by other considerations is a long-standing challenge of risk management, as evidenced by the accidents at BP Texas

BOX 3.5

Accidents that resulted from a combination of complexity and complacency

Macondo Oil Drilling Platform (Gulf of Mexico, 2010) The Macondo disaster of 20 April 2010, in the Gulf of Mexico, stemmed from the loss of control of an oil well, resulting in a blowout and the uncontrolled release of oil and gas (hydrocarbons) from the well. The accident resulted in the deaths of 11 workers and caused a massive, ongoing oil spill into the Gulf of Mexico (U.S. Chemical Safety Board, 2016a).

BP Texas City (USA, 2005). On 23 March 2005, a series of explosions occurred at the BP Texas City refinery during the restarting of a hydrocarbon isomerisation unit. Fifteen workers were killed and 180 others were injured (BP Refineries Independent Safety Review Panel, 2007).

Experts have noted that these two accidents were caused by severe organisational failures, which had remarkably similar causality, including (1) multiple system operator malfunctions during a critical period in operations, (2) required or accepted operations guidelines not being followed ('casual compliance'), (3) neglected maintenance, (4) instrumentation that either did not work properly or the data interpretation of which gave false positives, (5) inappropriate assessment and management of operations risks, (6) multiple operations conducted at critical times with unanticipated interactions, (7) inadequate communication between members of the operations groups, (8) a lack of awareness of risks, (9) diversion of attention at critical times, (10) a culture with incentives that provided increases in productivity without commensurate increases in protection, (11) inappropriate cost and corner cutting, (12) lack of appropriate selection and training of personnel, and (13) improper management of change (Carnes, 2011).

City (BP Refineries Independent Safety Review Panel, 2007) and the explosion and fire at the Macondo offshore drilling platform (U.S. Chemical Safety Board, 2016a). Both good and bad intentions can interfere with good risk decisions. For example, employees will tolerate bad conditions because they need jobs. Similarly, well-intentioned operators may delay maintenance and repairs on ageing sites to keep costs down and prevent the site from closing. Risk management efforts of some organisations and individuals can also by limited by systemic constraints, including a lack of political will and corruption, affecting both developed and developing countries. Economic and civil instability and a combination of long-standing cultural and structural deficiencies are a particular concern in developing countries. Economic pressure is a particular social driver that can put gains in chemical process safety at risk, particularly in the modern world when business circumstances change at a rapid pace. Instability in management and in business continuity has a knock-on effect on all aspects of risk management. In some situations, poor profit margins impose difficult decisions on various operations in terms of defining safety priorities when resources are stretched. However, there are also various trends in profitable companies, such as optimisation (operational efficiency) and the drive towards increasing shareholder value, that can undermine risk management when they are applied without due consideration of the impacts on risks.

5. **Increasing complexity.** Nowadays, change occurs more and more rapidly in all aspects of daily life. While individually the risks of technologies and associated hazards are generally known, the impacts of multiple and rapid changes in the way humans behave around them are difficult to assess and can to some extent constitute 'unknown unknowns'. As noted by Arstad and Aven (2017) for the Columbia Space Shuttle disaster, 'Always under pressure to accommodate tight launch schedules and budget cuts … certain problems became seen as maintenance issues rather than flight safety risks.' This situation is echoed in a number of the highly visible chemical accident disasters over the last few decades (e.g. BP Texas City (BP Refineries Independent Safety Review Panel, 2007), Buncefield (Howard, 2013), Macondo (U.S. Chemical Safety Board, 2016a)). Risks are not perceived as risk but rather as problems to work around. The prevailing trends are quickly replaced by new trends and existing technologies are quickly replaced by new technologies. Sites change ownership with considerable frequency (Kamakura, 2006), which is often accompanied by significant changes in management policies, work patterns, safety culture or other structures that guide norms of behaviour, and also contributes to an increasing decline in the corporate memory of accident risks (OECD, 2016). In reality, change occurs faster than the knowledge to understand how the change is affecting different aspects of our lives, including habits of living and working,

BOX 3.6

What can happen when governments are complacent.

The disastrous fire and explosion in the port of Tianjin, China, in 2015, is mainly attributed to lax safety procedures and a deliberate lack of government oversight. The owners of the storage and distribution company at the source of the accident somehow managed to persuade numerous authorities to look the other way with regard to permitting inspections and hazard control measures. The site began operations in 2014, handling and storing a variety of dangerous substances, many in volumes much higher than would be considered safe. According to the official investigation report, there was neither evidence that recognised safety standards were applied nor evidence that workers had been trained in handling hazardous goods. In addition to causing 165 deaths and injuries to nearly 800 people, 30 000 people in the surrounding community were evacuated (State Administration of Work Safety (China), 2016).

but also political, commercial and economic dimensions. As noted by Ruifeng et al. (2012), process controls and safeguarding equipment are more complex, thereby increasing newer risk that is often unforeseen. Both Mannan (2005) and Quarantelli (1997) also indicate that a correlation exists between the scale and complexity of process plants and major incidents. However, these and other modern trends are having significant consequences on safety and security, the long-term impacts of which are still not fully understood. Deeper understanding requires a multidisciplinary approach, despite the fact that the job market is exhibiting a tendency for increasing specialisation.

6. **Automation and information technology dependencies.** Twenty years ago, Quarantelli (1997) predicted that technological advances would reduce some hazards but make some old threats more dangerous, and cited computer technology as a kind of technology that represented a distinctly new danger. Indeed, the automation of activities traditionally performed by humans is a frequent adaptation of computer technology but it could in many circumstances create new risks in operations using dangerous chemicals. As pointed out by Lagadec and Topper (2012), society itself is still not clear about the full range of impacts of this innovation or other such 21st phenomena as the internet, the media explosion, social networking and smartphones. Moreover, as Taylor et al. (2016) suggest, an emphasis on interconnectivity and interdependence has become increasingly important, but when a failure occurs in one of the interconnected systems it can lead to major disruption. A further concern has emerged with the vulnerability of information technology systems to hacking or, even more simply, unforeseen potential for errors in the design and operation of automated systems that are increasingly interdependent across sites and accessed and operated by multiple users.

7. **Failure of risk management and risk assessment.** The EU eMARS (2012) and the U.S. Chemical Safety Board (2016a, b), for example, have produced many reports of recent past accidents for which the likelihood of the event occurring or the severity of its impacts could have been reduced with the application of actions within the hierarchy of risk management controls. Many of these reports also indicate a failure in the risk assessment process (e.g. that a risk assessment was not conducted, certain factors were discounted, lessons learned from previous events was ignored or that the risk associated with a change in operations was not considered). Indeed, many accidents also have been known to occur because of lack of follow-up after the monitoring and review of the functionality of the safety management system, such that the risk assessment was not updated after deficiencies in the risk assessment were discovered. Both organisations and individuals can fail to apply risk management principles, even when well established and part of training requirements. There is also often a lack of attention paid to inherent safety in which processes are designed without considering opportunities for risk reduction (chemical substitution, limiting volumes, exposure, etc.). This failure is sometimes attributed to various business and organisational trends cited in this paper, such as business climate and economic trends, organisational change and staff reductions, complexity and, sometimes, a loss of focus (complacency or 'organizational drift' (Taylor et al., 2015)); however, in other industries, particularly non-chemicals businesses and small companies, other factors, such as lack of awareness and education, are stronger influences.

8. **Corporate disconnect from risk management.** The globalisation of hazardous industries has increased both the physical and mental distance between headquarters and the sites they manage. Headquarters staff lose a tacit understanding of how sites experience chemical accident risks. For example, multinational sites can pose particular complexity when the culture and policy of the management is vastly different from that to which the site has been accustomed, especially if it is in a different country (European Commission Joint Research Centre, 2014). Corporate leaders also tend to oversimplify production safety risks (or risks are oversimplified for them) (Arstad and Aven, 2017; Taylor et al., 2015). It is assumed that new communication and automation technologies have universally positive trickledown benefits for all operations. For chemical accident hazards, the opposite is often the case. In particular, the trend towards short-term resource optimisation continues to have disturbing implications for chemical risk management. The tendency to outsource expertise and maintenance operations has already received considerable attention. There is also a preference in some companies to distribute limited expertise across many sites, so that access to critical safety expertise is

proportionately less available to sites. This phenomenon has been considered a significant factor in the Longford accident (Hopkins, 2014) as well as the catastrophic fire that occurred at the Buncefield storage site in 2005 (Howard, 2013).

9. **Insufficient risk communication and awareness.** Hazardous industries are introduced in locations with little attempt to communication and build awareness of the risks, to foster meaningful preparedness and planning, or to ensure that training and expertise are adequate for the responsibilities associated with the risk. This situation is particularly acute in developing countries where the desire for economic growth outweighs other decision factors. In many cases, risks are not so much accepted as ignored, encouraged by a historical lack of transparency in the political classes or society as a whole. When considered in context, the risk of fatal major accidents is also relatively small compared with the risks of poverty, disease and road traffic accidents and, therefore, may not receive the attention it deserves as a risk that is readily mitigated. The Enschede (the Netherlands) fireworks accident of 2000 (The Oosting Commission, 2001) and the accident in West, Texas (USA) (U.S. Chemical Safety Board, 2016b) are notable examples of how a lack of appropriate risk communication and awareness can contribute significantly to disasters.

10. **Resource and infrastructure deficiencies.** Many sites are compelled by a combination of circumstances and poor decisions to operate with less than adequate resources and infrastructure. In particular in developed countries, the physical infrastructures that underpin both public and private services are reaching the end of their normal lifespan (Quarantelli, 1997). A lack of resources generally leads to insufficient competence to manage risks (e.g. no chemical or mechanical engineer on site) or to improve degraded equipment or to apply safety management systems with rigor. Physical infrastructure can also be degraded by age or neglect, the latter of which was a key factor contributing to the catastrophic explosion and fire at the petroleum oil refinery at BP Texas City in 2005 (BP Refineries Independent Safety Review Panel, 2007). In many developing countries, it is common to start operations under less than ideal circumstances. The existing physical infrastructure may be degraded from years of neglect. There may be gaps in the education and risk awareness of local worker populations, as well as a limited availability of university-educated staff. Industries in developed countries also may suffer competency deficiencies due to declines in engineering students seeking career paths in traditional chemical process industries. Moreover, higher education in relevant engineering disciplines still excludes knowledge of chemical accident phenomena or basic principles of risk management.

11. **Deficiencies of the legal infrastructure.** In much of government and industry globally, management of chemical accident risks is focused on emergency preparedness, and strategies aimed at prevention and mitigation are not prioritised. Society as a whole exhibits a high risk tolerance owing to historically poor living and working conditions that consequently predisposes workers to accept and ignore workplace hazards. In many developing countries, there may be no legal framework to require and enforce minimum standards for process safety performance on chemical hazard sites. When a proper legal framework exists, regulators and operators lack the competence and resources to understand or enforce it. These circumstances have implications for developed countries in that companies may have sites in developing countries and their citizens may be customers of their products. However, even in developed countries, there is also a recognised pattern that governments do not often proactively engage in managing chemical accident risks until after a serious accident, or a number of serious accidents, occur. Notably, attention to chemical process safety in Australia gained widespread attention only after the Longford accident in 1998 (Hopkins, 2014), and in New Zealand following the mining accident in 2010 (Royal Commission on the Pike River Coal Mine Tragedy, 2012).

12. **Complacency in government and industry.** The longevity of chemical accident prevention and preparedness regimes in developed countries also leads many politicians and industry leaders to reduce their attention to chemical accident risks, threatening to undermine decades of risk-reduction progress. Sometimes called 'organizational drift' (Taylor et al., 2015), this phenomenon may occur in once-strong organisations and societies that allow their standards to erode over time without noticing their own decline. The perception that chemical accidents are no longer a threat eventually results in dramatic decreases in resources for enforce-

ment and risk management. Notably, there has been a dramatic lack of focus in modern times on process safety as an inherent operating requirement (not just because the legislation requires it). Government complacency can be manifested by lax application of permitting laws, reduced frequency of inspections and insufficient attention to land use and emergency planning. Complacency in industry is often evidenced by greater tolerance of deviations from accepted norms, such as process parameters, safety procedures and maintenance requirements. In developing countries, the problem is arguably worse. The vast majority of owners and operators of hazardous sites, even in large state-owned or multinational subsidiaries, are used to minimal management of chemical hazards on their sites.

3.12.4 Implications for future scientific study

The main topics that emerge as areas for further study and experimentation are listed and described below. Many are already the subject of projects in research institutes and collaborations within the international community.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society.

However, it is widely recognised that these problems, having proved so resistant to solutions, will require considerable reflection and patience to identify approaches that produce tangible improvements.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society through the following:

- Motivating corporate and government leadership. New models for the governance of hazardous industries should be explored and tested. These models should apply to corporate leadership and government alike, applying management philosophies supported by rigorous enforcement proportionate to the level and complexity of the risk. New strategies should be based on a mutual expectation between government and industry of overall corporate responsibility for maintaining risk resilience that goes far beyond the current compliance-based paradigm. Enforcement will need new (more evolved) strategies (e.g. nudge, push, force) to drive industrial practice. Concepts such as recovering the profits of illegal/unsafe activity to remove the economic advantage may also be a step forwards. Fears that the process industries could potentially have parallels to the banking crises (2008 onwards) in terms of poorly understood risks have triggered the development of the Organisation for Economic Co-operation and Development (OECD) publication Corporate Governance for Process Safety — Guidance for Senior Leaders in High Hazard Industries, an important new tool for industry and government addressing this topic (OECD, 2012).

- Systematic accident reporting, data collection and exchange. There needs to be a concentrated effort to build national and international chemical accident registers and to promote accident exchange between industries and countries. The availability of reliable chemical accident statistics will allow academics, politicians and the media to understand the magnitude and nature of chemical accident risks and identify appropriate risk-reduction measures.

- Promoting positive safety culture both industry-wide and in society. The chemical processing industries should focus serious attention on developing a positive safety culture industry-wide, such that it is resilient in the face of change, particularly in the economy and site management. Psychologists should work with industry and governments to foster risk awareness and sensitivity among citizens. An informed safety-sensitive society can help to support a broader mandate to insist that companies exercise greater corporate responsibility for reducing the risks associated with their operations.

- Heightened commitment to the Plan–Do–Act cycle in chemical process safety management. After an accident has occurred, a common finding is that a potential risk factor had been identified and ignored. In keeping with improved safety culture, guidance and training on safety management policy and performance indicators need to put more emphasis on incorporating lessons learned from past events and audit findings on deficiencies in risk management into process hazard assessments and the safety management system as quickly as possible.

- Risk management in SMEs in the chemical business. There are subcategories of SMEs in the chemical business, each of which has elevated risk for different reasons. The most challenging intellectually are the SMEs that know their risks and take care to manage them but still have accidents. More research is needed on why accidents occur in SMEs, including geographic and economic differences that may influence these risks, and on strategies to reduce them.

- Risk management in non-chemical businesses. Similarly to SMEs, studies to develop strategies and guidance to support risk management in many of these industries are still needed. There are a number of examples of this work, such as the U.S. Environmental Protection Agency's Supplemental Risk Management Program Guidance for Ammonia Refrigeration Facilities. More analysis and dissemination of lessons learned from accidents in such locations is also needed.

- Business-sector risk-reduction initiatives on a global scale. Oil and gas, extractive industries, industrial parks and large-scale chemical production should be the focus of a global collaborative effort between industry, government and aid organisations to reduce chemical accidents in these industries.

- Risk assessment models that address new technologies and complexity. Some researchers (e.g. Taylor et al., 2015; Travers, 2016) are already proposing models by which to assess risks associated with complexity. These models need to be tested and developed further. In addition, research is required to characterise and quantify various emerging risks, including those associated with the increasing use of automation and the outsourcing of critical safety functions, ownership change, how culture and competence profiles in different countries can affect chemical accident risk and other emerging concerns mentioned in this paper.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles, in particular in relation to:

- Mechanical integrity. All too often, maintenance and repairs of equipment and infrastructure are considered dispensable when inconvenient for profit or production goals. The underlying causes should be studied and new approaches adopted that provide stronger motivation, including risk assessment requirements and government-operator interfaces (e.g. permits, inspections), for reinforcing mechanical integrity as an operating requirement.

- Management of change. This safety principle is particularly challenging because time pressures and a human preference for expediency undermine its consistent implementation. Finding methods that help companies and individuals to recognise change when a change can elevate risk is an important part of resilience engineering and a significant aspect of the 'resonance' factor described by Leonhardt et al. (2009). Resonance is a quality that explains how disproportionately large consequences can arise from seemingly small variations in performance and conditions.

- Learning lessons from accidents and failures. Industries and sites need to learn from, and remember, past accidents. Corporate memory loss, across-industry, is not an appropriate excuse. A greater investment is needed in projects to develop strategies to learn and remember, with a particular emphasis on collaborations between industry, government and academia. According to Patterson (2009), both industry and government struggle with barriers that tend to undermine systematic extraction and communication and lessons learned and there needs to be a renewed effort to overcome these barriers. As noted by Hailwood (2016), companies operating major hazard facilities should establish systems that not only ensure reporting and learning from their own accidents and near misses, but also make use of databases and reports from the accidents of others. Each country should also make resources available to investigate accident causes and lessons learned, as well as to collect and document this knowledge and make it accessible to third parties.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term, enabled by:

- Greater access to risk management knowledge and tools. Risk management is always specific to a site. Few sites have exactly the same risks, even if they produce the same products, since the physical characteristics of the location, structures and equipment are important elements of the risk. Considerable future mechanisms are needed to ensure good management practice for all kinds of operations and to make equipment available in an easy to read format, taking account of the many different languages in which they might be needed.

- Access to risk assessment competence. Both operators of hazardous sites and regulators need to know the type and severity of accidents that could occur and have a realistic understanding of the control measures needed to ensure that the risk of such accidents is minimised. Cheap and easy access to interactive consequence assessment, risk mapping and quantitative assessment tools is urgently needed in all areas of the world.

- Strategies to combat a labour market deficient in appropriate expertise. Industry and academia need to continue to push for standardised process safety curriculums associated with chemical engineering and chemistry in particular, as well as with environmental management and other related disciplines to some extent. Multinational companies operating in developing countries need to be aware that competence and experience in risk management may be far less available than in Europe or the United States, and process operations need to be adjusted accordingly (Zhao et al., 2014). In all parts of the world, industry and the professional engineering community should do far more to support occupational and process safety education and training to produce more qualified professionals capable of identifying and managing risks in design and daily operations.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries, and special emphasis should be placed on the following:

- Building basic awareness of chemical risks and how to manage them to developing countries. Basic training in chemical risks and safe chemicals management is badly needed. The remarkable efforts of numerous international organisations such as UNEP, UNECE (United Nations Economic Commission for Europe), UNEP-OCHA and the WHO, among others, are underfunded and far too fragmented to have significant impacts, despite smart management and promising results from recent initiatives. Meaningful progress is possible only with substantial commitments involving UNDP, United Nations Institute for Training and Research, the World Bank and the European Commission as well as Regional Economic Commissions in the context of a coordinated and comprehensive long-term strategy.

- Resilience and risk awareness building. There has been considerable success with stakeholder involvement approaches such as UNEP APELL to manage risks at a local level within a systemic national and international regional strategy. A number of tools, including those produced by the OECD (2003) and UNEP (2010), already exist to guide developing countries on how to build a comprehensive and effective chemical accident risk prevention and preparedness programme. The clear next step is to identify and deploy mechanisms by which to provide significant and sustained support to countries that are ready to take steps towards establishing such programmes.

- Fostering regional and international networks and collaborations on chemical accident risk management. A critical mass of policy and technical initiatives at both regional and international level, creating a constant pressure and giving developing countries easy access to expertise and technical support, is a way to establish a new norm. A number of international organisations (e.g. UNECE, 2014)) have reported increasing success with such approaches but they are barely implemented for chemical accident prevention programmes in regions such as Asia and Africa.

- Improving performance measures for interventions. Fund administrators generally lack objective measures by which to evaluate suitable candidates for chemical accident prevention programmes that may target the specific needs of and provide continued support to achieve meaningful results. Further refinement and testing of capacity-building performance indicators, and methods for qualitative assessment (e.g. level of political will, key drivers of change) such as those currently in development by the JRC (Baranzini et al., in progress), can lead to better targeting of such initiatives. These could also be useful for developed countries.

3.12.5 Conclusions and key messages

Recent accident trends provide evidence that the world is nowhere near reducing the risk of industrial accidents to acceptable levels. While developed countries have shown marked improvements, particularly in reducing the average number of fatalities associated with chemical accidents, the overall rate of major accidents with other serious impacts remains high. Throughout the world, accidents continue to stem from violations of well-known safety management principles. Such failures can only sometimes be explained by complexity and a misfortunate combinations of events; very often they may be due, entirely or in part, to incompetence, a lack of awareness or outright negligence. Many experts are exasperated that management practices and attitudes are so vulnerable to other influences and resist improvement.

In conclusion, accepted norms of industry, government and society are undermining good risk management. This finding has a number of important implications for the direction of future research, policy development and the role of government and industry in reducing accident risks.

Partnership

The findings confirm overwhelmingly that the traditional approach in which stakeholders stick to their traditional rules is not going to fix the problems in question. It is no longer possible that industry works alone to define and implement good risk management practice. Policymakers can no longer simply set performance standards and then step aside. Observations from academics, particularly in the social sciences, need to find their way into both industry and government approaches to chemical accident risk.

Knowledge

The control of chemical accident risk is very often undermined by the cultural norms and expectations associated with how government and business are expected to act, and a lack of knowledge and awareness about chemical accident risks in society in general. Combatting these forces requires new thinking about how our businesses and governments are working with these risks. As such, the essence of the change is that all society must recognise part ownership of chemical accident risk, and ownership implies both a certain responsibility for, and power to prevent, such risk. This finding in turn requires that the new approach to controlling chemical accident risks is to change culture with education and awareness.

Innovation

The recommendations in this paper suggest a paradigm change in the way the EU and the developed world in general approach chemical accident risk. Solutions must encompass a broader vision of risk ownership and boundaries of influence, recognising that the role of industry does not end beyond the fence line, that offsite forces can influence onsite risks and that society's responsibility may need to extend beyond traditional geographic boundaries. If the system is the problem, the solutions lie in changing the system.

3.13 Technological risk: nuclear accidents

Emmanuel Raimond, *Gryffroy Dries, Andrej Prošek*

3.13.1 Introduction

Nuclear accidents, if their consequences are not mitigated, have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility. Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce such risks as far as possible, but there is always a residual risk, as demonstrated by the recent Fukushima Dai-ichi accident.

This subchapter presents some of the fundamental principles applied in nuclear safety. These fundamentals are introduced with the idea that they can be transposed to other technological or natural risks. It then summarises some important lessons from the three accidents that influenced the nuclear industry significantly: Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011).

The subchapter then explains risk assessment methodologies and describes the current efforts for risk reduction, from plant design to emergency plans.

Nuclear accidents have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility.

In conclusion, this subchapter proposes some perspectives on research that can support risk assessment or help in accident management in this area. Understanding the interactions between nuclear facilities and their environment appears to be a crucial and transversal issue.

3.13.2 Nuclear safety framework

In European Member States, Council Directive 2014/87/Euratom of 8 July 2014 (EU, 2014) provides a general framework to be applied in relation to nuclear safety. This framework is consistent with the Safety Fundamentals established by the International Atomic Energy Agency (IAEA) (IAEA, 2006), and the main recommendations provided by the Western European Nuclear Regulators Association (directive for reactors in operation (WENRA, 2014) and new reactors (RHWG, 2013)).

Some important issues are summarised below.

The IAEA (2006) has defined one fundamental safety objective, namely to protect people and the environment from harmful effects of ionising radiation, and 10 fundamental safety principles:

1. The primary responsibility for safety must rest with the person or organisation responsible for the facilities and activities that give rise to radiation risks.

2. An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.

3. Effective leadership and management for safety must be established and sustained in organisations concerned with, and facilities and activities that give rise to, radiation risks.

4. Facilities and activities that give rise to radiation risks must yield an overall benefit.

5. Protection must be optimised to provide the highest level of safety that can reasonably be achieved.

6. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.

7. People and the environment, present and future, must be protected against radiation risks.

8. All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

9. Arrangements must be made for emergency preparedness for and response to nuclear or radiation incidents.

10. Actions to reduce existing or unregulated radiation risks must be justified and optimised.

Those safety fundamentals are then expressed in more technical requirements or concepts in each country or at European level (EU, 2014) or in the IAEA Safety Standards.

Some important concepts are summarised below. They can obviously be transposed to other risks induced by human activities.

Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce nuclear risks as far as possible.

The safety culture shall be encouraged by the management, at all levels in the licensee organisations: this shall include ensuring that their actions discourage complacency and encourage an open reporting culture as well as a questioning and learning attitude with a readiness to challenge acts or conditions adverse to safety (see WENRA, 2014, for example).

The defence-in-depth approach (INSAG, 1996; IAEA, 2016) is considered a key concept by which to reach an appropriate level of protection from nuclear risk. For example, Council directive 2014/87/Euratom (EU, 2014) includes the following statements:

[…] safety activities are subject to, as far as reasonably practicable, independent layers of provisions, so that in the event that a failure were to occur, it would be detected, compensated or corrected by appropriate measures. The effectiveness of each of the different layers is an essential element of defence-in-depth to prevent accidents and mitigate the consequences should they occur. Defence-in-depth is generally structured in five levels. Should one level fail, the subsequent level comes into play. The objective of the first level of protection is the prevention of abnormal operation and system failures. If the first level fails, abnormal operation is controlled or failures are detected by the second level of protection. Should the second level fail, the third level ensures that safety functions are further performed by activating specific safety systems and other safety features. Should the third level fail, the fourth level limits accident progression through accident management, so as to prevent or mitigate severe accident conditions with external releases of radioactive materials. The last objective (the fifth level of protection) is the mitigation of the radiological consequences of significant external releases through the off-site emergency response.

The design of nuclear power plants (NPPs) is based on a deterministic approach: initiating events (deviations from normal operation, incidents, accidents, hazards) are postulated and used to design all systems, structures and components (SSCs) with design rules that should ensure significant safety margins. Such an approach must be completed by a probabilistic approach that allows considering more exhaustively the combinations of events (initiating events, system and human failures) that could lead to an accident. This is explained below.

The European regulators consider that a continuous improvement of the safety of NPPs is a good practice that should be promoted: this means that NPPs are submitted to periodic safety reviews, possibly associated to safety objectives enhancement. Such periodic safety reviews shall concern all safety issues, including plant ageing, the modifications of the NPP environment (e.g. climatic changes) and any upgrading or modernisation of the plant. The result of such a process should be such that NPPs become progressively safer.

There are a number of organisations at the international level that share experience and good practices, including:

- the IAEA
- the OECD Nuclear Energy Agency (NEA)
- the European Nuclear Safety Regulators Group (ENSREG)
- the Western European Nuclear Regulators Association (WENRA)
- the European Nuclear Installations Safety Standards Initiative (ENISS)
- the World Association of Nuclear Operators (WANO)
- the European Technical Safety Organisation Network (ETSON)
- the Association of the Heads of the European Radiological protection Competent Authorities (HERCA).

The European Commission also promotes a high level of nuclear safety through its tasks in the preparation of Euratom directives. The European Commission JRC coordinates or participates in several nuclear safety scientific research and technical support projects. The Euratom Framework Programs (now Horizon 2020) also provide financial support to European nuclear research and training projects, including risk assessments and nuclear safety projects. For example, the ASAMPSA_E (Advanced Safety Assessment methodologies: extended PSA) project, on risk assessment practices, which is mentioned in this subchapter, and the European Severe Accident Research Network of Excellence (SARNET) have been supported by European Commission funding. Some projects deal with emergency management (EURANOS, NERIS-TP). Through the EU Instrument for Nuclear Safety Cooperation, European and international safety standards are also promoted in third countries.

3.13.3 Lessons from past events

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly. They led European Union to set out a common European maximum permitted levels of contamination in foodstuffs following a nuclear accident and develop an early warning system ECURIE, while many EU Member States have installed the networks of radiation measurement stations that have been integrated in an EU-wide monitoring system EURDEP.

3.13.3.1 Three Mile Island, 1979

The Three Mile Island accident occurred on 28 March 1979 in Pennsylvania, USA. Although some risk studies had emerged before 1979 (US NRC, 2016), this accident demonstrated the importance of having an awareness of the potential for core melt accidents among NPP designers and operators. The accident was caused by an incident on the reactor steam generator feedwater system, which led to the automatic reactor tripping. Considering all existing safety systems, this event should not have been the cause of an accident, but some maintenance errors (e.g. wrong valve positions), additional equipment failure (one primary circuit safety valve did not respond to a closure signal from the control room), and a misunderstanding of the reactor status by the operators in the control room led to the melting of the reactor core. This led to significant radioactivity release in the reactor containment vessel. The accident progression was stopped when the operators restarted the injection of water into the reactor vessel.

The offsite radiological consequences were very limited thanks to the design features of the reactor containment vessel. Nevertheless, the accident caused extreme anxiety in the population, despite the fact that the recommendation of evacuation by the nuclear authorities was later cancelled by the governor of Pennsylvania.

Many lessons have been learned from this accident (IRSN, 2013) relating to, for example, the following:

- NPP operator procedures (a combination of symptom-based and event-based procedures is now preferred);
- NPP operator training (accident computer simulation training, accident drills, etc.);
- NPP control room design (reliability of information displayed, alarm processing, etc.);
- additional emergency operating procedures are needed for situations that are not anticipated in the

initial design (loss of the main electrical supply, loss of ultimate heat sink, filtered containment venting procedure, etc.);
- the reactor containment vessel is of prime importance and shall be reinforced where possible;
- precursors of accidents (incidents with no serious consequences) shall be analysed systematically to identify possible weaknesses; this may lead to modifications in NPP design or operation;
- emergency preparedness is of prime importance, with local and national emergency response teams able to support control room operators and to coordinate protective actions for the population;
- research to understand accident progression in the case of a severe accident is needed, and appropriate mitigation strategies shall be developed;
- probabilistic safety assessments (PSAs, see below) shall be developed to identify accidents associated with multiple failures or common cause failures, for which safety improvements may be needed.

3.13.3.2 Chernobyl, 1986

On 26 April 1986 at 01:24, the RBMK (Reaktor Bolshoy Moshchnosti Kanalnyy, i.e. high power channel-type reactor that is a class of graphite-moderated nuclear power reactor designed and built by the Soviet Union) type reactor 4 at the Chernobyl NPP, which had been in service since 1983, exploded in an accident during a technical test. The initial design of the RBMK reactors had some significant weaknesses from a safety standpoint. In particular, they were highly unstable at certain power ranges, the emergency shutdown system had too long a response time and there was no containment around the reactor. In addition, the lack of sufficient preparation for the conditions required for the planned test, and the lack of time in which to complete it, meant that operators did not follow all the operating rules. They also violated these rules by suppressing some important safety systems.

The explosion sent radioactive materials contained in the nuclear reactor core into the atmosphere, to altitudes of more than 1 200 metres. The radioactive plume then propagated in the European atmosphere, then worldwide, and caused the contamination of territories at different level. The areas of Belarus, Ukraine and Russia, which received depositions of caesium-137 exceeding 37 000 becquerels per square metre after the accident, cover a surface area of approximately 150 000 km2 with more than 5 million inhabitants. The accident had huge impacts on the environment (contamination of ground, rivers, forest, agriculture products, etc.), the ecosystem (transfer of contamination through the food chain or agricultural cycles), human health (especially for the 'liquidators' who worked to limit the consequences of the accident and for inhabitants of contaminated areas) and the economy and society in general. Many research programmes have been devoted to the study of the impacts of this accident.

A number of lessons have been learned from this accident (IRSN, 2011), including:

- a new perception and understanding of the consequences of such an accident;
- the importance of emergency preparedness to face such events (national emergency response organisations have been reinforced in most countries);
- the importance of transparency and providing information to the public: an EWS, ECURIE (European Community Urgent Radiological Information Exchange), has been elaborated that allows each country to immediately inform all EU Member States in the event of an accident in one of its nuclear facilities; a dedicated European Directive (EU, 1989) defines common requirements on informing the general public in the event of a radiological emergency and some countries have significantly reinforced the legal basis for such transparency (e.g. France; see French Nuclear Safety Authority, 2006); an International Nuclear Event Scale has been defined to ensure clear understanding of the severity of various events;
- the need for common European maximum permitted levels of contamination in foodstuffs following a nuclear accident, which have been set out in a related Council Regulation issued in 1987 (Euratom, 1987);
- for the overall radiological surveillance of the environment, EU Member States have installed radiation measurement stations; these national networks have been integrated in an EU-wide monitoring system EURDEP (European Radiological Data Exchange Platform; a standard data-format and network for exchanging radiological monitoring) which is managed by the European Commission;
- in terms of plant design and operation, the accident has promoted the

safety culture (under an interrogative and prudent approach, the test at the origin of the accident would not have been carried out) and the importance of the appropriate application of the defence-in-depth concept (despite human error, other lines of defence should have prevented such a disaster).

For new reactors, European regulators consider that such accidents with large radioactive release shall be 'practically eliminated' and they require an appropriate demonstration of the various safety features (RHWG, 2013). This requirement has a considerable impact on reactor design features.

3.13.3.3 Fukushima Dai-ichi, 2011

The Fukushima Dai-ichi accident was initiated by the Great East Japan earthquake that occurred on 11 March 2011 with a magnitude of 9. It caused a tsunami that struck the Japanese coasts, with waves exceeding 10 metres. The devastation in Japan was considerable: more than 15 000 people were killed, 6 000 were injured and 2 500 reported missing, and the destruction of buildings and infrastructure was considerable.

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly.

The earthquake did not threaten the Fukushima Dai-ichi NPP's safety functions, but the resulting tsunami submerged the NPP's platform and led to the loss of the ultimate heat sink and most internal electrical supplies. Four out of six reactors stayed in long-term station black-out conditions. The site staff, despite their best efforts and considerable courage, could not prevent core melt at units 1, 2, and 3 and the resulting hydrogen explosions and large radioactive release in the environment. This caused a nuclear catastrophe in addition to the earthquake and tsunami impacts. Although the winds were mostly directed towards the sea during the accident, the ground contamination by the radioactive plume led to the evacuation of 80 000 inhabitants (a number that rose after a 'voluntary' evacuation starting on 25 March) and had huge impacts for agriculture, ecosystems, the economy and society in general in the region of Fukushima. The contamination of the ocean by liquid releases also had impacts on the fishing industry. The IAEA report (2015) provides a description of the accident, its consequences and all remediation efforts.

The accident led European countries and many others to develop a stress test programme to assess the capacity of NPPs to withstand extreme conditions (ENSREG, 2012). The robustness of NPPs has been assessed in terms of three major topics:

- protection against extreme external hazards (earthquake, flooding, etc.);
- NPP controls in the event of a loss of ultimate heat sink or electrical supply;
- severe accident management protocols.

Most NPP operators have decided to implement additional provisions on their utilities to further increase their robustness and the protection of population. The European regulators and the IAEA have also promoted the concept of 'design extension conditions' (IAEA, 2016; WENRA, 2014). The idea is to extend the basic design of NPPs to account for more adverse conditions for which a reactor can still be maintained in a safe state, or for which a severe accident (with core damage or spent fuel damage) can be controlled to recover a stable state without any significant radioactive release into the environment.

After the Fukushima Dai-ichi accident, most countries decided that NPP reinforcements must be able to face extreme conditions. Such reinforcements should enable the following:

- site protection against hazards (extreme flooding, winds, etc.);
- implementation of additional protected (bunkered) safety systems or the reinforcement of some existing structures, systems and components;
- implementation of additional fixed or mobile equipment to allow plant stabilisation in extreme situations;
- implementation of new infrastructure and equipment for emergency response management (reinforced emergency building, reinforced mobile equipment storage, additional communication and transport means, improved protection against radioactivity);
- more staff responsible for emergency actions;
- improvement of severe accident management strategies and, for some NPPs, the implementation of new equipment.

In relation to emergency preparedness and response, existing and reinforced requirements have been integrated into the revision of the European Basic Safety Standards directive (EU, 2013); the directive gives an increased focus on the need for international cooperation. The emergency management plans have been improved or are in revision in many countries (see HERCA-WENRA scheme for severe accidents, change in pre-planning radii for evacuation, sheltering and iodine distribution). Research in this area was promoted via the PREPARE and the recently started CONCERT project.

This has led to post-Fukushima action plans on a national level as well as to enhancements of the safety standards at international (IAEA, WENRA, etc.) or national levels.

Although NPP modifications have been decided, the Fukushima Dai-ichi accident has led to an increased interest in the study of natural and man-made hazards that could threaten a nuclear site and in the development of an on-site and off-site emergency response organisation that is capable of facing any complex situation.

3.13.3.4 High-amplitude external hazards at nuclear power plant sites

Nuclear power plants should be designed to withstand any high-amplitude external hazards that could threaten safety functions. Nevertheless, a number of high-amplitude events have caused problems at some nuclear sites. This is an important challenge for the safe operation of NPPs, and many countries, such as France, include a re-assessment of external hazards at each 10-year periodic safety review. If the safety margins appear to be reduced in light of the most recent knowledge (e.g. on earthquake, flooding risks or more general climatic changes), then NPP reinforcements can be decided. To illustrate this topic, a survey has been carried out by the ASAMPSA_E project (ASAMPSA_E, 2013) on more than 80 high-amplitude external hazards that have been experienced by NPPs or other facilities and high-amplitude external hazards described in the IAEA Incident Reporting System (IRS) database. Table 3.7 provides some external hazards that could be experienced by nuclear facilities identified by ASAMPSA_E.

Meteorological events are the most frequent, followed by biological infestation events. ‘Low air temperature’ seems to be the most recurrent hazard, followed closely by ‘Lightning’ hazards. Infestation with marine organisms has been observed more often than infestation with vegetable materials (such infestation may threat the ultimate heat sink of NPPs).
The Fukushima Dai-ichi accident showed the importance of the combinations of hazards. This fact was also identified in France during an event at Le Blayais NPP in 1999 (a combination of a storm, high tide and waves led to the partial submersion of the NPP platform). This event led to the significant reinforcement of certain French NPPs against flooding, but perhaps not to an international awareness of the importance of combinations of hazards in risk assessments.

All the above show the importance of enhanced investigations of all credible external hazards, including all their possible correlations and combinations. This has led to the analysis of the impact of ‘rare events’, which is a challenging activity for the engineering sector.

3.13.4 Safety assessment methodologies

The design of NPPs follows a set of rules and practices that should ensure a high level of safety. Standards have been developed, then improved, in a number of areas, from high-level considerations (IAEA, 2016; WENRA, 2014; RHWG, 2013) to more technical ones (e.g. rules for mechanical design).

An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions that are applied to design all safety-related SSCs of the NPP. These accident conditions result from initiating events (equipment failure, human errors, internal or external hazards) leading to NPP transients, which are then analysed using specific conservative assumptions to ensure safety margins. The examination of this set of accident conditions using conservative assumptions is the so-called deterministic safety assessment. The methods that are applied must be sufficiently simple for the feasibility of the design and its safety demonstration, and sufficiently robust to ensure that the NPP and its organisation can be resilient to any event during plant operation.

To improve the safety demonstration, and as a complementary approach to the deterministic approach, probabilistic safety assessments (PSAs) are developed. A definition of the three levels of PSA can be found in IAEA Safety Standards SSG-3 (IAEA, 2010a) and SSG-4 (IAEA, 2010b):

'PSA provides a methodological approach to identifying accident sequences that can follow from a broad range of initiating events and it includes a systematic and realistic determination of accident frequencies and consequences. In international practice, three levels of PSA are generally recognised:

1. *In Level 1 PSA, the design and operation of the plant are analysed in order to identify the sequences of events that can lead to core damage and the core damage frequency is estimated. Level 1 PSA provides insights into the strengths and weaknesses of the safety related systems and procedures in place or envisaged as preventing core damage.*

2. *In Level 2 PSA, the chronological progression of core damage sequences identified in Level 1 PSA are evaluated, including a quantitative assessment of phenomena arising from severe damage to reactor fuel. Level 2 PSA identifies*

TABLE 3.7

External hazards that could be experienced by nuclear facilities

<table>
<tr><td>Earthquakes
Tsunamis
Ground subsidence</td><td>Flooding
High tides
Storm surges
Wind waves
High river levels/flow
Spring runoff (from mountains)</td><td>High winds
Hurricanes
Tornados
Projectiles driven by high winds
Salt storms</td><td rowspan="2">Blackout
Electrical disturbance transmitted by the external power grid
Malware computer programs or computer viruses
Electromagnetic interference
Disturbance by high-frequency radio signals
Oil spills
Transport accidents
Aircraft crashes
External fire due to human activity
External explosion
Corrosive liquids or gases
Toxic liquids or gases
Radioactive releases
Pandemics/severe epidemics</td></tr>
<tr><td>Biofouling
Jellyfish infestation
Small fish infestation
Mollusc infestation
Shell infestation
Vegetable material in the heat sink
Reeds intrusion
Algae
Rat infestation</td><td>Low water temperature
Frazil
Ice in cooling water
Frost</td><td>Lightning
Solar flares, solar storms, geomagnetic storms</td></tr>
<tr><td>Sand deposits
Silting
Small rocks
Sediments</td><td>Low air temperature
High air temperature
Low river levels</td><td>Extreme rain
Heavy snowfalls
Wet snow
Atmosphere moisture
Hail
Freezing rain</td><td>Forest fire</td></tr>
</table>

ways in which associated releases of radioactive material from fuel can result in releases to the environment. It also estimates the frequency, magnitude, and other relevant characteristics of the release of radioactive material to the environment. This analysis provides additional insights into the relative importance of accident prevention, mitigation measures, and the physical barriers to the release of radioactive material to the environment (e.g. a containment building).

3. *In Level 3 PSA, public health and other societal consequences are estimated, such as the contamination of land or food from the accident sequences that lead to a release of radioactive material to the environment.*

PSAs are also classified according to the range of initiating events (internal and/or external to the plant) and plant operating modes that are to be considered.'

The PSA methodology is based on event tree methodologies, which are conceptually simple but highly complex in detailed applications. This is due to the number of SSCs in a NPP, the variety of initiating events, the possible equipment and human failures, the interdependencies between events, the uncertainties in data (hazards modelling, equipment failure probability, human failure probability, physical phenomena progression, SSCs behaviour in unplanned circumstances, etc.). A PSA modelling exists for almost all NPPs. Their quality is progressively improving, thanks to periodic updates and experience sharing. For example, the OECD-NEA working group risk (WG-Risk) collects and shares international experience in this area.

Although this approach is quite advanced for NPPs, PSA experts recognise in general that these studies still have some weaknesses and continual improvements are performed. One weakness is often the completeness of initiating events and hazards considered, which varies from one PSA to another.

Standards have been developed to design NPPs that should ensure a high level of safety. An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions. To improve the safety demonstration probabilistic safety assessments are developed.

The ASAMPSA_E project was initiated in 2013 to help increase the scope of existing PSAs. For this project:

'An extended PSA (probabilistic safety assessment) applies to a site of one or several Nuclear Power Plant(s) (NPP(s)) and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core and spent fuel storages, other sources) on the site, taking into account all operating states for each main source and all possible relevant accident initiating events (both internal and external) affecting one NPP or the whole site.'

Some general lessons can be identified (Raimond, 2016):

- an extended PSA is still an objective for most PSA teams working on NPPs: no NPP site currently has a PSA that covers:
  -full-power and all reactor shut down-state initial states
  -all sources of radioactivity
  -all relevant types of initiating events (internal and external)
  -multi-unit accident management
- there is a need to enlarge the analysis scope in terms of the NPP, the neighbouring reactors or other industries, the environment at a medium scale;
- the risk metrics to be used are still a topic for discussion, especially if the objective is to calculate some 'global risk';
- PSA experts have to decide, for each NPP, which initiating events should be included in the PSA. Criteria are applied to identify risk significant events but, for some initiating events (e.g. high-amplitude earthquakes or combined extreme weather conditions), high uncertainties exist in both their frequency and amplitude; in such cases, the PSA approach is questionable;
- the geosciences fail sometimes to calculate both frequencies and features of some rare (extreme) natural events for PSA with reasonable uncertainty bounds; this is, in fact, a societal concern and progress in these areas should be expected;
- the study of the impact beyond design hazards may require additional methodologies (e.g. impact of beyond design lightning strike);
- PSAs have been applied to single NPPs; PSAs for multiple NPP sites have rarely been undertaken; the feasibility and interest of such

studies are ongoing issues;
- the application of PSAs (or extended PSAs) in decision-making processes is still a topic for harmonisation: for example, the recent interest in rare extreme events functions as a reminder of the need to take into account uncertainties in decision-making processes.

3.13.5 Risk reduction, a multiform activity

As explained above, European nuclear stakeholders apply the concept of continual safety improvement. This is done with a risk-reduction perspective. PSA has a role in this process, but many other considerations are taken into account. Risk reduction is in fact a multiform activity that cannot be reduced to a simple list. Some examples are proposed below but they cover only a limited number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

For new reactors, the protection of the population in the event of a severe accident is paramount, as indicated by WENRA (2014):

' reducing potential radioactive releases to the environment from accidents with core melt, in short and long term, by following the qualitative criteria below:
- *accidents with core melt that would lead to early or large releases of radioactive material should be practically eliminated;*
- *in the event that accidents with core melt do occur, design provisions should have been be made so that only limited protective measures in area and time are needed for the public (e.g. no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long term restrictions in food consumption) and sufficient time must be available to implement these measures.'*

Several safety authorities request that utilities upgrade existing reactors to meet, as far as possible, the objectives for new reactors. In particular, it shall be postulated that severe accident may happen and that, in such cases, accident mitigation strategies shall be implemented. This obviously contributes to some degree of risk reduction, at least if the other existing safety features are not degraded as a result of ageing.

Risk reduction is a multiform activity that cannot be reduced to a simple list. There are a number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

Research activities are very important to ensure the continued interrogation of existing practices, to develop new knowledge and to promote the application of new knowledge in safety improvements. Some examples are described here but, in fact, there are numerous topics of interest (e.g. see NUGENIA, 2013):

- the reassessment of hazards is an important issue during periodic safety review; as explained above, for natural hazards, there are topics where geosciences provide highly uncertain information due to remaining uncertainties for rare events but, nevertheless, even if the quantification of hazard features is difficult, reinforcement of NPPs can be decided based on the most recent knowledge;
- the analysis of NPPs' responses in the event of an accident using simulation tools capable of providing best-estimate information for the design verification of SSCs or the development of operating procedures;
- the analysis of SSCs' response (fragility analysis) in the event of hazards (earthquake, flooding, fire, lightning, etc.);
- techniques for in-service inspection to check the capability and conformity to safety standards of all key safety equipment (e.g. pipe welding control, risk informed inspection, plant walkdowns);
- research on severe accident progression;
- research on accident precursors;
- research on human factors and organisations: how to evaluate the efficiency of organisations to ensure the efficiency of all human activities (during NPP design, construction, normal operation, modernisation, control, accident management, etc.).

The emergency response is also a crucial factor during accident management. This concerns the site in question (to help manage a complex situation at a local and national level, to ensure the dissemination of transparent information), the public authorities (to decide protective actions for the populations, to disseminate information transparently to the public) and international exchanges (the consequences of a nuclear accident are transnational; rescue solutions can often be found at the international level, and immediate and transparent communication is expected from any country facing a nuclear accident). As mentioned above, many research activities support progress in emergency response capabilities, for example on source term prediction, simulations of radioactivity transfer in environment, rules for the protection of populations, rules for agriculture management and communication during and after the accident (see EURANOS, NERIS-TP and PREPARE projects).

In addition, it is also recognised that the organisation of the control of nuclear activities by official bodies (in general nuclear safety authorities and technical safety organisations) and the relationship between the industry and these official bodies are of primary importance in risk reduction. Relationships with NGOs also have to be considered carefully.

We can mention, as an example, some values generally shared by the safety authorities or the Technical Safety Organisations, namely competence, independence, rigor, transparency impartiality, proactivity or initiative. The efficiency of the control of nuclear activities is another topic for exchanges at the international level.

3.13.6 Conclusions and key messages

Partnership

To conclude, we wish to highlight the importance of the multiform activities conducted to prevent any accident or to limit its consequences should one occur. The fundamental safety principles and the defence-in-depth approach underlie these multiform activities, which intend to enhance the nuclear safety requirements, the design features of nuclear facilities, the quality of construction, all human activities during normal operation and, in response to accidental situations, the continuous safety improvement and the control by appropriate bodies.

Knowledge

The efficiency of the emergency response plans at local, national or international levels and of the related international cooperation remains a challenge for the nuclear industry, and good practices can be shared with other activities. In parallel, research on the resilience of human organisations when facing complex situations can be promoted in the nuclear industry and in many other areas.

Innovation

The nuclear industry has still to face many challenges to maintain and improve the safety of operating and new reactors. Among these challenges are the human and organisational factors (training and education, generation renewal, changes in competences, evolution of requirements and regulation, modernisation programmes, the organisation's efficiency, etc.), the ageing of the nuclear facilities and the financial context.

If some challenges are very specific to nuclear activities, others are fully cross-connected to other human activities. For example, the study of high-amplitude natural hazards has become increasingly important since the Fukushima Dai-ichi accident, and efforts are being made to reinforce nuclear facilities if needed. Understanding and predicting these natural hazards is a societal concern and progress in geosciences is expected. To support safety studies for nuclear facilities, seismic faults identification and modelling, the quantification of correlated natural hazards (typically during extreme weather conditions) or the regional analysis of the consequences of such natural hazards are topics of interest for which knowledge should be improved.

3.14 Technological risk: Natech

Elisabeth Krausmann*, Ana Maria Cruz, Roland Fendler, Ernesto Salzano*

3.14.1 Introduction

The past few years have seen a number of natural disasters accompanied by major damage to industrial facilities and other infrastructures. In March 2011, a tsunami struck a Japanese NPP, causing a nuclear meltdown, and raging fires and explosions at oil refineries in the wake of the massive earthquake that triggered the tsunami also made the global headlines. Other recent examples of major disasters include Hurricane Sandy in 2012, which caused multiple hydrocarbon spills and releases of raw sewage, the damage to industrial parks during the Thai floods in 2011, or Hurricanes Katrina and Rita in 2005, which wreaked havoc on the offshore oil and gas infrastructure in the Gulf of Mexico (Krausmann and Cruz, 2013; Cruz and Krausmann, 2008, 2009).

These events clearly demonstrated the potential for natural hazards to trigger fires, explosions and toxic or radioactive releases at hazardous installations and other infrastructures that process, store or transport dangerous substances. These technological 'secondary effects' caused by natural hazards are known as 'Natech' (Natural-hazard-triggered technological) accidents (Krausmann et al., 2017a). They are a recurring but often overlooked feature of many natural-disaster situations and have repeatedly had significant and long-term social, environmental and economic impacts, including supply-chain disruptions (Figure 3.57). It is important to note that natural-hazard impacts on commercial districts or residential areas where lower quantities of hazardous materials are present are also a safety concern.

Natural hazards can cause multiple and simultaneous releases of hazardous materials over extended areas, damage or destroy safety barriers and systems, and down lifelines often needed for accident prevention and mitigation. These are also the ingredients for cascading disasters. For this reason, successfully controlling a Natech accident has often turned out to be a major challenge, if not impossible, where no prior preparedness planning had taken place.

Natech accidents can have serious consequences, including cascading events. While their risk is increasing, they are not adequately addressed in DRM.

Unfortunately, disaster risk-reduction frameworks do not fully address technological hazards in general or Natech hazards in particular. In addition, chemical accident prevention and preparedness programmes often overlook the specific aspects of Natech risk, which has caused a lack of dedicated risk-assessment methodologies and guidance for industry and authorities on how to manage these risks both onsite and offsite.

This is aggravated by the expected increase of future Natech risk due to worldwide industrialisation, climate change, population growth and community encroachment in areas subject to natural hazards (Krausmann and Baranzini, 2012).

This subchapter gives an overview of the state of play in Natech risk reduction in the EU and globally; it highlights existing gaps in Natech risk reduction and makes recommendations on how to close these gaps.

While natural-hazard triggered nuclear accidents also qualify as Natech events (see Chapter 3.13), this subchapter focuses on Natech risk in terms of non-nuclear hazardous industrial activities.

3.14.2 Forensic analysis of Natech accidents and lessons learned

Post-accident analysis is a valuable tool to recreate the dynamics of accidents and to draw conclusions on the most prominent damage mechanisms and hazardous materials release paths, particularly vulnerable storage and process equipment types, as well as on the hazardous materials most commonly involved in these types of accidents. For this reason, efforts have been made to systematically collect and analyse information on the causes and dynamics of Natech accidents to support scenario development and the design of better protection options. In order to facilitate this process and to overcome the deficiencies of conventional industrial accident databases with respect to Natech accidents, the European Commission has set up the eNATECH database for the systematic collection and analysis of Natech accident data and near misses. The database exhibits the more sophisticated accident representation required to capture the characteristics of Natech events and is publicly accessible (eNATECH, 2015).

Lessons can be learned in all phases of risk and accident management, from prevention and preparedness to response and recovery. Analyses of single accidents produce immediate lessons specific to the event, while analyses of a set of similar accidents from a broader data pool yields lessons learned that are more widely applicable. The latter type of study facilitates, for example, the identification of commonly occurring causes of accidents involving specific substances or industries, which may not be easily recognisable within a single occurrence. This analysis also lends itself to identifying technical and organisational risk-reduction measures that require improvement or that are missing.

3.14.2.1 General lessons learned

The analysis of Natech accidents across different types of natural hazards showed that there are certain commonalities regardless of the

FIGURE 3.57

Hydrocarbon releases at a refinery during floods in Coffeyville, USA, in 2007.
Source: photograph courtesy of the Kansas Wing of the Civil Air Patrol

natural-hazard trigger. Studies have indicated, for instance, that storage tanks at atmospheric pressure, and in particular those with floating roofs, appear to be particularly vulnerable to earthquake, flood and lightning impacts compared with other types of industrial equipment (Krausmann et al., 2011). While no systematic studies for other types of natural hazards are available, individual case histories seem to support this conclusion in the case of storms or heavy rain (Bailey and Levitan, 2008; Godoy, 2007).

From an industrial safety perspective, the high susceptibility of storage tanks to natural-hazard impacts is problematic, as these plant units often contain large quantities of crude oil, gasoline or other types of flammable liquid hydrocarbons. It is therefore unsurprising that many Natech accidents involve hydrocarbon releases that have ignited and escalated into major fires or explosions (Table 3.8). In addition, with hazardous materials releases possibly occurring from several sources at the same time, an increased ignition probability, coupled with simultaneous damage to safety barriers and systems including the frequent loss of lifelines needed for process control or firefighting, the likelihood of cascading disasters is also higher for Natech events than for conventional industrial accidents.

3.14.2.2 Lessons learned from Natech accidents due to earthquakes, floods and lightning

Most Natech accident analyses have focused on accidents triggered by earthquakes, floods or lightning. Priority was given to these hazards because of the generally greater severity of Natech events caused by earthquakes (Antonioni et al., 2009), and the high frequency of accidents initiated by floods and lightning in EU Member States and OECD Member Countries (Krausmann and Baranzini, 2012). Systematic analyses of the dynamics and consequences of Natech accidents caused by other natural hazards are scarce, although other natural hazards, such as tsunamis, extreme temperature, high winds or landslides have also caused Natech accidents.

Hydrocarbon storage tanks are found to be particularly vulnerable to natural-hazard impact, which increases the cascading risk. Safety barriers are usually also affected by natural hazards and are unavailable for accident mitigation.

The main damage and failure mechanisms of industrial structures and hazardous equipment during earthquakes are direct shaking impact, ground deformation and liquefaction (Figure 3.58). The impact ranges from structural damage without the release of hazardous materials, such as shell buckling, sloshing damage or anchor-bolt stretching, to damage with loss of containment, caused, for instance, by the failure of flanges or pipe connections, shell and roof failures or tank overturning and collapse (Krausmann et al., 2011). The analyses also showed that during earthquakes it is common that several loss-of-containment events occur simultaneously. This increases the likelihood of cascading accidents. The analyses also highlighted the vulnerability of safe-

TABLE 3.8

Substances mainly involved in flood-triggered Natech accidents according to an analysis by Cozzani et al. (2010)

Hazardous substance category	No. of accidents
Oil, diesel fuel, gasoline; liquid hydrocarbons	158
Propane, butane, LPG	12
Fertilisers	11
Acid products	7
Cyanides	5
Oxides	5
Ammonia	5
Chlorine	3
Explosives	3
Calcium carbide	3
Soap and detergents	1

ty barriers (e.g. catch basins around tanks or sprinkler systems) to seismic loading.

In the case of floods, the main damage and failure mechanisms are the displacement of equipment due to buoyancy and water drag, as well as the impact of floating objects. This can break connections between pipework and equipment, cause pipelines to rupture or lead to tank collapse or implosion (Krausmann et al., 2011). Once a hazardous material has been released, the presence of the floodwaters aggravates the accident by acting as a vector for spreading the released toxic or flammable materials over wide areas. This can also increase the likelihood of domino accidents while simultaneously creating further risks in the areas surrounding the damaged facility (Figure 3.57). The analysis of flood-triggered accidents also showed that released substances can react violently with the floodwaters, thereby creating secondary toxic or flammable gases from often less dangerous precursor chemicals (Cozzani et al., 2010).

The analysis of lightning-triggered Natech accidents highlighted two different types of impact mechanisms: (1) direct impacts, causing structural damage to equipment, or the ignition of flammable vapours by the lightning strike (e.g. at the rim seal of atmospheric storage tanks); and (2) indirect impacts, which can trigger loss of containment, e.g. via process upsets due to power outage and power dips and impacts on electrical control and safety systems (Renni et al., 2010).

For a detailed discussion of lessons learned from Natech accidents due to a wide variety of natural hazards, the reader is referred to Krausmann and Salzano (2017).

FIGURE 3.58

Collapse of a dryer and severing of connected pipes at a fertiliser factory hit by the 2008 Wenchuan earthquake in China.
Source: photograph courtesy of E. Krausmann

3.14.3 Status of Natech risk management in European Union Member States and in OECD Member Countries

3.14.3.1 European Union

In the EU, major (chemical) accident risks are regulated by the provisions of the so-called Seveso Directive on the control of major-accident hazards and its amendments (European Union, 2012; see also Chapter 3.12). Following a series of Natech and other major chemical accidents (e.g. the spill of cyanide-laced tailings from a dam breach due to heavy rainfall and rapid snowmelt, or the release of chlorine from a flooded chemical facility), it was decided that an amendment of the Seveso Directive was needed to close remaining gaps. The latest amendment now explicitly addresses Natech risks and requires that environmental hazards, such as floods and earthquakes, be routinely identified and evaluated in an industrial establishment's safety report (European Union, 2012). Awareness of Natech risks in Europe has been growing ever since.

A recent survey among Seveso regulatory bodies aimed to assess the status of Natech risk management in the EU (Krausmann and Baranzini, 2012). The results of the survey showed an increasing awareness of the potentially disastrous impacts of natural hazards on chemical facilities. However, the survey also highlighted a number of gaps in Natech risk reduction, as well as related research and policy challenges.

Over half of the survey respondents indicated that their countries had experienced one or more Natech accidents in the period 1990-2009. The main accident triggers were lightning, low temperatures and floods. Considering the recurrence of Natech accidents, the survey results suggest that the legal frameworks for chemical-accident prevention have not always been effective. The survey participants expressed their belief that industries in many EU Member States may not consider Natech risks appropriately in their facility risk assessment, with potentially low preparedness levels as a result. The survey also revealed strong differences between the actual Natech accident triggers and the natural hazards perceived to be of concern, highlighting an incongruity between actual causes and risk perception.

The recurrence of Natech accidents has also raised doubts about the adequacy of design codes and standards for hazardous installations with respect to natural-hazard impact, as well as about the associated protection measures in place. The ultimate objective of these codes and standards is the preservation of life safety and, hence, the prevention of building collapse. While in itself an important goal, the preservation of a building's structural integrity is not necessarily sufficient to prevent the release of hazardous materials under natural-event loading.

The survey identified a number of key areas for future work for industry, regulators, and science and engineering. The majority of survey respondents called for the development of guidance on Natech risk assessment for industry with the highest priority, followed by the preparation of Natech risk maps to inform land-use and emergency planning by identifying a region's Natech hotspots.

3.14.3.2 The Organisation for Economic Co-operation and Development (OECD)

Parallel to the survey on the status of Natech risk management in the EU, OECD Member Countries were polled on the same subject. The OECD results showed a similar trend as in the EU and highlighted the same gaps (Krausmann and Baranzini, 2012). The majority of OECD survey respondents expressed their belief that there is a clear need to improve current regulations and fill existing gaps to fully address Natech risk reduction. Similar to the EU survey, they called for the development of natural-hazard and Natech risk maps, methodologies for and guidance on Natech risk assessment for industry and communities, as well as the training of authorities on Natech risk reduction.

Natech accidents continue to happen, which raises doubts about the effectiveness of existing safety legislation, as well as about the adequacy of design codes and standards for natural-hazard impact at hazardous installations.

One of the main international guidelines considering Natech risks are the OECD Guiding Principles for Chemical Accident Prevention, Preparedness and Response (OECD, 2003), the application of which is the subject of an OECD Council Recommendation. Given that the 2003 revision of the Guiding Principles considered only some aspects of Natech risk management, the OECD Working Group on Chemical Accidents decided to address the issue more comprehensively by including a Natech project into its 2009-12 work programme to identify existing gaps and develop targeted recommendations for Natech risk reduction.

As a final outcome of the OECD Natech project, a Natech Addendum to the Guiding Principles was issued (OECD, 2015). This addendum includes numerous recommendations for government and industry that address the inclusion of Natech risks in the drafting of regulations, rules and standards, their enforcement and implementation, and other activities in support of effective Natech risk management. With pipelines being at risk owing to natural hazards, the Natech Addendum also advocates the consideration of Natech risks in pipeline safety.

As a follow-up to the first Natech project, the OECD included a second Natech project in its 2017-20 work programme, which focuses on the implementation of recommendations from the first project and on improving international cooperation in Natech risk management.

3.14.4 Natech risk assessment

Risk analysis is an important tool by which to estimate the risk level of a hazardous activity. Quantitative risk assessment (QRA) in particular allows the identification of system weaknesses, the prioritisation of safety measures in terms of their importance for risk reduction, or the estimation of a facility's overall risk level, summarised in a risk figure. This risk figure can then be compared with prescribed risk acceptance target levels, where existing, to show that risks are adequately controlled in fulfilment of regulatory requirements (see Chapter 2.1).

3.14.4.1 General methodology

The identification of potentially Natech-prone areas and the determination of the associated risks are the first steps towards managing Natech risks. As Krausmann and Baranzini (2012) note, hardly any Natech risk maps exist in EU Member States and OECD Member Countries, and the development of a Natech risk analysis and mapping capability is considered a high-priority need by authorities to effectively reduce Natech risks.

There is a lack of consolidated Natech risk assessment tools, and extensions to traditional risk analysis need to be made to take into account the characteristics of Natech events.

Regardless of the risk-analysis approach chosen, extensions to both qualitative and quantitative risk analysis need to be made to take into account the characteristics of Natech events. Hence, specific damage models to assess the severity and probability of equipment damage due to a natural event, and a procedure to account for the possibility of simultaneous hazardous materials releases from more than one process or storage unit are needed. Simple damage models are available for a limited number of equipment categories (storage tanks, some types of process equipment) and in particular for earthquake impact. The inclusion of these damage models in QRA case studies has demonstrated the importance of considering earthquake-triggered accident scenarios for ensuring the safety of the facility itself and the surrounding population and environment (Antonioni et al., 2007; Campedel et al., 2008). Therefore, natural hazards can be important risk contributors at hazardous facilities and must be adequately considered in the risk-analysis process.

An in-depth discussion of the individual steps in Natech risk assessment, including the treatment of cascading events, can be found in Krausmann (2017).

3.14.4.2 Methods and tools for Natech risk assessment

The surveys discussed in Chapter 3.14.3 highlighted a lack of methodologies and tools for Natech risk analysis and mapping, which has so far hampered the appropriate inclusion of this type of risk into industrial risk assessment. Following calls by government to close this gap, the European Commission (JRC) developed the RAPID-N framework for rapid Natech risk assessment and mapping, which can be used to quickly identify Natech risk hotspots (Girgin and Krausmann, 2017, 2013). RAPID-N is a unique, semi-quantitative tool that allows the rapid analysis of Natech risks at local (single installation) or regional (multiple installations) level. This web-based tool is freely available via prior user registration and authorisation (RAPID-N, 2017). Figure 3.59 shows an example output of RAPID-N.

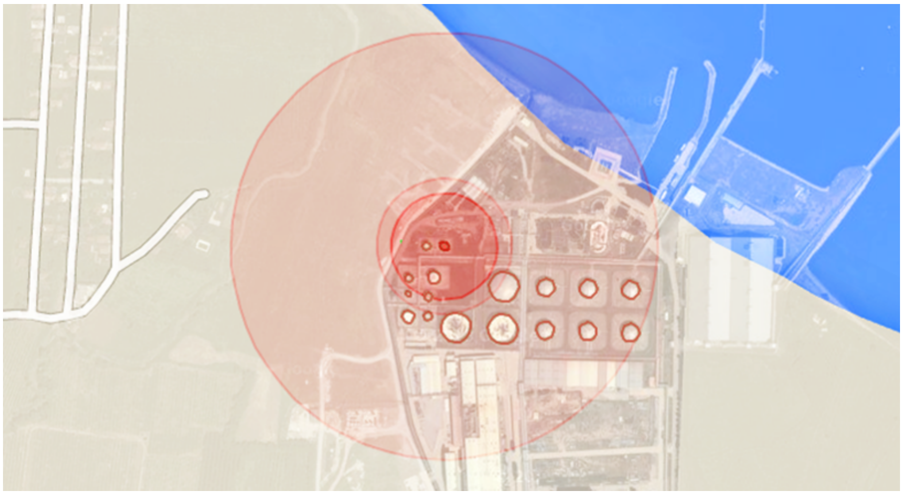
RAPID-N supports different natural hazards and industrial equipment types by design. It estimates and maps Natech risk in a web-based environment and can support land use and emergency planning, as well as Natech damage and consequence analysis immediately after a natural event. The latter in particular is fundamental for first responders who require an assessment of the dangers of secondary hazards from industrial plants following a natural disaster before dispatching rescue teams. It could also provide a means by which authorities may warn the population in the vicinity of an installation of imminent problems.

The current version of RAPID-N supports earthquake Natech risk analysis and mapping for fixed chemical installations, such as refineries or storage tank farms, and onshore pipeline networks. In the next release of the tool, floods will be included as additional Natech accident triggers. Additional short-term upgrades that are under way are (1) the inclusion of individual and societal risk calculations in addition to impact zones to move towards a more quantitative treatment of the problem, and (2) the implementation of an automated analysis function that will allow Natech risk analysis for facilities in the RAPID-N database immediately following the occurrence of a major natural event. Through this function, competent authorities, first responders and other interested parties can be quickly alerted to potential Natech accidents to ensure that fast protective action is taken if required.

While RAPID-N currently follows a semi-quantitative approach for analysing and mapping Natech risks to ensure a quick assessment with a minimum of data, the University of Bologna has developed a Natech module for its software package ARIPAR-GIS to characterise the Natech risks of single facilities in a quantitative way (Antonioni et al., 2017). This approach is more detailed than that of RAPID-N; however, it requires a significant number of data for the assessment process. The output of ARIPAR-GIS is individual risk and societal risk from Natech accidents caused by earthquakes and floods.

FIGURE 3.59

RAPID-N example output for the release and ignition of a flammable substance caused by a hypothetical Istanbul earthquake scenario. The circle endpoints indicate the point up to which second-degree burns would be received for different release scenarios.
Source: courtesy of European Commission (JRC)



3.14.5 Natech risk reduction

Past near misses have shown that Natech risk reduction generally pays off, and facilities that have benefited from natural-hazard specific design and the implementation of Natech risk-reduction measures have fared better during natural events (e.g. Cruz and Steinberg, 2005). Where these measures were inadequate or totally lacking, damage was more severe or even catastrophic.

Problem areas that stand out in most Natech accidents are related to insufficient prevention and preparedness, often caused by the grossly inadequate design bases of hazardous installations in natural-hazard prone areas due to a failure to acknowledge the specific requirements of process equipment under natural-hazard loads, the absence or weak enforcement of safety regulations, and a lack of guidance on how to address the problem of Natech risks in the industry. In addition, there is the misconception that engineering and organisational protection measures in place to prevent and mitigate conventional industrial accidents would also protect against Natech events. In fact, the very natural event that damages or destroys industrial buildings and equipment can also render inoperable engineered safety barriers (e.g. containment dikes, deluge systems) and lifelines (power, water for firefighting or cooling, communication) needed to prevent an accident, mitigate its consequences and keep it from escalating. There is, therefore, a need for Natech-specific additional safety measures to accommodate the characteristics of Natech accidents, which require targeted prevention, preparedness and response.

3.14.5.1 Structural prevention and mitigation measures

In general, structural risk-reduction measures for technological risks use engineering solutions, such as safety valves or containment dikes, for accident prevention and mitigation. In this context, prevention refers to passive and active actions or measures put in place to reduce the likelihood of damage and the occurrence of a hazardous materials release, while mitigation refers to actions or measures implemented to lower the impact of hazardous materials releases if they cannot be prevented.

Experience from past Natech accidents and the associated lessons learned have led to the development of recommendations for reducing Natech risks for accident scenarios from a wide variety of natural hazards. For example, in earthquake-prone areas, flexible tank-pipe connections should be used given that the breaking of rigid connections has often led to releases (Figure 3.60). Anchoring or restraining equipment could effectively avoid displacement and keep equipment containing hazardous materials intact. The vulnerability of safety barriers (e.g. catch basins around tanks or sprinkler systems) is particularly apparent during earthquakes. Critical active and passive safety barriers should, therefore, also be designed to withstand the forces of the expected earthquake.

Natech risk reduction requires targeted prevention, preparedness and response, including Natech-specific safety measures, the implementation of which was found to pay off.

FIGURE 3.60

Flexible steel pipe on a large oil tank in an earthquake-prone area. Source: photograph courtesy of A.M. Cruz

The risk of flood-triggered Natech accidents can be minimised, for example, if hazardous equipment is anchored or otherwise restrained to prevent floating and displacement by floodwaters. Indirect flood impacts via short-circuiting of electrical equipment that affects safety-critical systems can be reduced by protecting systems from wave loading and water intrusion. This can be achieved by waterproofing and appropriate design. The lifting of flammable waste oil in plant drainage systems due to flooding can be prevented by segregating the drainage systems for waste flammable substances and surface run-off water.

With respect to reducing the Natech risk from lightning strikes, the rim seal of atmospheric floating-roof tanks is the most likely point of ignition, and the seal should therefore be regularly checked and maintained. Furthermore, partial or total onsite power outage and power dips can lead to process upsets and thereby indirectly to hazardous materials releases. Internal backup systems should provide emergency power to those processes from which dangerous conditions can result during power loss (Krausmann et al., 2011).

Many more structural Natech prevention and mitigation measures for different natural hazards and equipment types are discussed in detail in Cruz et al. (2017).

3.14.5.2 Organisational prevention and mitigation measures

In contrast to structural measures, which use engineered physical solutions for prevention and mitigation, organisational measures are administrative programmes and controls put in place to reduce risks. Organisational protection measures include staff training, the implementation of safety practices and procedures, including the monitoring of safety performance, educational and awareness-raising campaigns and the establishment of safety policies and laws. Since technical protection measures can never entirely eliminate hazards from a hazardous installation, organisational control is needed to support protection goals.

An in-depth discussion of organisational Natech risk-reduction measures and approaches is provided in Krausmann et al. (2017b). The following sections provide examples of such measures.

3.14.5.3 Natech risk governance

From a Natech point of view, risk governance is becoming exceedingly important in light of increasing industrialisation coupled with emerging hazards, such as climate change. Since natural hazards can impact large areas at the same time, an integrated risk-governance approach involving all stakeholders is needed that addresses the safety of individual industrial installations as well as the potential interactions with neighbouring installations, lifelines and nearby communities. The Great East Japan earthquake and the Thai floods in 2011, for example, highlighted the need to better understand infrastructure-failure interdependencies and the governance of the associated risks.

TABLE 3.9

Effectiveness of Natech-specific early warning based on the warning time to warn and action time tact.
Source: Salzano et al. (2009)

twarn/tact	Characteristics	Effectiveness
<< 1	Short warning time or slow preventive action	Low: little time to implement preventive action
≈ 1	Warning time similar to time needed for preventive action	Medium: some preventive action possible prior to natural-event impact
>> 1	Long warning time or fast preventive action	High: sufficient time for preventive action even if time-consuming

3.14.5.4 Emergency planning

Natech accidents caused by major natural events pose a tremendous challenge for emergency response owing to:
- possible multiple and simultaneous hazardous materials releases over extended areas, a scenario for which emergency responders are usually not trained and equipped;
- competition for scarce emergency response resources for providing aid in natural disaster areas and for combatting the Natech accident;
- hampering of search and rescue operations as a result of toxic releases, fires and explosions;
- inapplicability of standard civil-protection measures such as evacuation or shelter;
- reliance of industry on external lifelines and emergency-response resources for managing a Natech accident rather than preparing a 'standalone' emergency plan.

In order to increase preparedness for Natech accidents, emergency plans for hazardous industry should consider natural-hazard risks. Plant-internal emergency plans for mitigating hazardous materials releases should assume that safety barriers are absent or non-functional and off-site response resources are not available, requiring backup lifelines to control the Natech accident. Off-site emergency plans need to take into account the eventuality of toxic releases, fires and explosions impacting the population and the rescue operations and the need for evacuation in a situation where transport routes might be compromised. An assessment of the vulnerability of the emergency response resources is also called for in the context of Natech risk reduction.

Emergency plans at both plant and community level should be periodically reviewed and tested to ensure that they remain up to date. This is of particular importance in times of climate change, which might require updates to the assumptions on which the emergency plan is based.

3.14.5.5 Early warning

Early warning is usually not available or practicable for reducing Natech risks, as warning times for some natural hazards are too short for preventive action at hazardous facilities. Salzano et al. (2009) contend that the effectiveness of Natech early warning systems is defined by the ratio of the available warning time and the time needed to implement preventive action (Table 3.9).

For earthquakes, for example, warning times range from fractions of seconds to only a few seconds, which makes early warning for earthquake Natech accidents rather impractical. In this case, the earthquake-resistant design of hazardous installations should be prioritised.

The situation is different for river floods, for which warning times can range from hours to days, leaving ample time and opportunity to mitigate the Natech risk, for example by implementing plant shut-down, depressurising equipment or transferring hazardous substances from predicted on-site inundation zones to safer locations. If tsunamis are generated in the far field, the warning lead time should permit the actuation of prevention actions, as for floods.

Interestingly, Bouquegneau (2007) also suggests that early protective actions, such as disconnecting sensitive equipment or stopping hazardous processes, are possible for lightning hazards by using information from meteorological lightning location systems.

3.14.6 Conclusions and key messages

Past Natech accidents have clearly shown the vulnerability of hazardous industrial activities to natural-hazard impact, with often major consequences on health, the natural environment, and the local, regional or global economy owing to asset damage and the associated business downtime. Some of these accidents have also dramatically demonstrated the increased risk of cascading effects and the challenges faced by emergency responders.
The good news is that awareness of Natech risks is increasing worldwide and first attempts to systematically assess and control this risk are being made. Nevertheless, a number of research and policy gaps related to Natech risk reduction remain that require addressing in a concerted effort of regulators, industry and the research community.

Partnership

In many countries, there is legislation that regulates hazardous industrial activities, and in some cases Natech risks are explicitly addressed. It is important that these regulations be enforced. Where missing, dedicated legislation for reducing Natech risks should be developed and implemented. At the same time, risk communication between industry and all levels of government should be improved to ensure that communication related to Natech risks flows freely and effectively to realistically estimate the risk. Public–private partnerships could facilitate the linking of science, practice and policy in support of Natech risk reduction.

Knowledge

Further awareness-raising efforts are needed to help stakeholders recognise the vulnerability of hazardous installations during natural-hazard impact. In this context, climate change must be a factor in the assessment, as it might change natural-hazard severities and frequencies and thus render the design basis of installations and equipment inadequate. In addition, plant workers, civil protection authorities and those in charge of chemical-accident prevention need to receive targeted training to be able to handle the challenges that are associated with Natech accidents.

Risk assessment is an important tool by which to identify safety gaps and prioritise safety-relevant interventions at a facility. There are no consolidated methodologies for Natech risk assessment, and research should focus on the development of Natech risk assessment methodologies and tools for different natural hazards, as well as related guidance at the industry and community levels. Data on accidents and near misses crucial for learning lessons and scenario building are often closely guarded by industry for fear of negative repercussions on their activity. Authorities should promote and facilitate the sharing of Natech accident data by companies to support future risk reduction.

Recommendations

The last few years have seen a number of natural disasters that have been accompanied by major damage to industrial facilities. These events have demonstrated the potential for natural hazards, such as earthquakes, floods, storms, etc., to trigger fires, explosions and toxic or radioactive releases at hazardous installations that use or store hazardous substances. These so-called Natech accidents are a recurring but often overlooked feature of many natural-disaster situations. In addition, chemical and nuclear activities are an increasingly important source or risk of such accidents owing to increased industrialisation and urbanisation.

Unfortunately, disaster risk-reduction frameworks have not commonly addressed technological risks. The Sendai Framework for Action recognises the importance of technological hazards and promotes an all-hazards approach to disaster risk reduction. This includes hazardous situations arising from man-made activities due to human error, mechanical failure and natural hazards.

Chemical risk

Chemical accidents continue to occur relatively frequently in industrialised and developing countries alike, which raises questions about the adequacy of current risk-reduction efforts. The causes underlying chemical accidents are largely assumed to be systemic. Most chemical accidents today are caused by violations of well-known principles for chemicals risk management, which have led to insufficient control measures.

From the forensic analysis of chemical accident reports, a number of underlying causes have emerged, one or several of which can affect a chemical installation to create conditions conducive to disaster. These causes include:

- A lack of visibility due to a lack of published statistics on accident frequency and a reporting bias towards high-consequence accidents, which are a mere fraction of the many smaller chemical accidents that occur each week.
- The challenge to manage across boundaries, when chemical and mechanical engineers commonly assigned to chemicals risk management have little training in human or organisational factors.
- A failure to learn lessons from past accidents and near misses.
- Economic pressure and a trend towards optimisation, which can undermine risk management when decisions are made without due consideration of their impacts on safety risks.
- Failure to apply risk-management knowledge by both individuals and organisations due to a lack of awareness and education, or inattention to inherent safety.
- Insufficient risk communication and disconnection from risk management due to the globalisation of hazardous industries, which places a distance between corporate leaders and the sites they manage.

- Outsourcing of critical expertise or distribution of limited expertise over many sites, making it less accessible when needed.
- Governments do commonly not proactively engage in managing chemical-accident risks until after a serious accident, and accident management is focused on emergency preparedness and response rather than prevention.
- Complacency in government and industry due to the incorrect perception that chemical accidents are no longer a threat, thereby causing a decrease in resources for enforcement and risk management.
- Based on the identified accident causes, a number of areas for further study and experimentation to reduce chemical accident risks should be explored, and it is recommended that the following occur:
- Motivation of corporate and government leadership by exploring new models for risk governance, and promotion of a positive safety culture by fostering risk awareness. Enforcement will need a new strategy to drive industrial safety practice.
- Promotion of systematic accident reporting, data collection and exchange to raise awareness of the potential consequences of chemical accidents. These data should be used to learn lessons from accidents and near misses.
- Development of strategies to combat labour market deficiencies related to process-safety expertise.
- Creation of cheap and easy access to risk-management knowledge and tools, including to risk-assessment competence urgently needed in all areas of the world.
- Building of awareness of chemical risks and how to manage them in developing countries.
- Fostering of regional and international networks and collaboration on chemical accident risk management to create pressure and give developing countries easy access to expertise and technical support.

Nuclear risk

Accidents at nuclear facilities, regardless of the accident trigger, have the potential to cause a disaster. In the EU, a nuclear safety framework aims to ensure that people and the environment are protected from the harmful effects of ionising radiation. The basis of this framework is the defence-in-depth approach, a key concept by which to reach an appropriate level of protection from nuclear risks, and an adequate safety culture.

After several major nuclear accidents, safety assessment methodologies have been continuously improved, and the design of a NPP follows a set of rules and practices that ensure a high safety level. At the design stage, a set of accident conditions is identified that can result from different initiating events, and this set is examined using a conservative, deterministic safety assessment. This is complemented by a PSA, which provides a methodological approach to identifying accident sequences that can follow from a wide range of initiating events, as well as to determining accident frequencies and consequences. The challenge is to make certain that the list of considered initiating events is complete.

Many different protective activities form the basis of ensuring the safety of nuclear facilities, both during normal operation and in the case of accidents. However, the nuclear industry still faces a number of challenges that need to be addressed. The following are therefore recommended:

- Further assess the impacts on the safety of nuclear activities of human and organisational factors (e.g. training, management of change, evolution of regulations and associated requirements), of ageing effects on nuclear facilities and of financial concerns.
- Improve knowledge of the identification and modelling of natural hazards to support safety studies for nuclear facilities.
- Share good practice on emergency responses at local, national and international levels between nuclear and non-nuclear industrial activities to increase the efficiency of emergency-response plans.
- Promote research on the resilience of human organisations in the face of complex situations in nuclear industries and other areas with similar requirements.

Natech risk

Natech accidents are a technological 'secondary effect' of natural hazards and have caused many major and long-term social, environmental and economic impacts. National and international initiatives have been launched to examine the specific aspects of Natech risk and to support its reduction.

The forensic analysis of Natech accident records has allowed the preparation of lessons learned across different triggering natural hazards that support the reduction of Natech risks. This includes the setting up of a dedicated Natech accident database to foster the easy and free sharing of accident data. Accident analyses also show that there is an increased risk of cascading effects during Natech accidents. In general, Natech risk reduction pays off, and several structural, as well as organisational, accident prevention and consequence mitigation measures are available.

Studies on the status of Natech risk management in EU Member States and OECD Member Countries have highlighted deficiencies in existing safety legislation and the need to consider this risk more explicitly. Conventional technological risk-assessment methodologies need to be expanded to be applicable to Natech risk assessment and only a very few methodologies and tools are available for this purpose.

With respect to the effective reduction of Natech risks, several research and policy gaps still need to be closed in a collaborative effort between regulators, industry and academia. Public–private partnerships could be helpful in this context. More specifically, it is recommended that:

- Existing legislation that regulates hazardous industrial activities should be enforced. Where missing, legislation for reducing Natech risks should be developed and implemented.
- Risk communication on Natech risks should be improved between industry

and all levels of government to ensure a free and effective flow of information that enables a realistic assessment of the associated risk.
- Government should promote and facilitate the sharing of Natech accident data for future Natech risk reduction.
- An inventory of best practices for Natech risk reduction should be set up and disseminated to all stakeholders.
- Research should focus on the development of Natech risk assessment methodologies and tools, as well as guidance on Natech risk management for industry and at the community level.
- Competent authorities and workers at hazardous installations should receive targeted training to be able to handle the challenges associated with Natech accidents.
- Additional awareness-raising efforts are needed to help stakeholders recognise the vulnerability of hazardous industry to natural-hazard impact. In this context, the effects of climate change on natural-hazard frequencies and/or severities need to be factored in.

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Chapter 4

Communicating disaster risk

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4 Communicating disaster risk

CONTENTS

Introduction

The communication of disaster risk is inherently a social process. It aims to prevent and mitigate harm caused by disasters, prepare the population for a disaster, disseminate information during disasters and nurture the recovery. Disaster risk communication plays a vital role during all four stages of the disaster cycle: mitigation and prevention, preparedness, response and recovery. This chapter aims at translating scientific insights in disaster risk communication to decision-makers to eventually enable communities to respond effectively to damaging events. It builds on the idea that using insights from (communication) science is essential for effective decision-making to improve lives, livelihoods and health (Aitsi-Selmi et al., 2016; Dickinson et al., 2016).

Risk communication in disasters has traditionally been a one-way, unilinear and top-down transfer of information from authorities to the public (Krimsky, 2009). The current literature on disaster risk communication, in contrast, sees communication between authorities and the public about disasters as an outcome of interactions. Although there is no closure on the effectiveness of new communication strategies due to the lack of systematic studies (Bradley et al., 2014), there is growing empirical evidence that a two-way dialogue between the public and professionals is more effective than the traditional unidirectional model of disaster risk communication (Treurniet et al., 2015). The non-linear, multi-directional approach to risk communication is consistent with a political landscape where the legitimation is gained through negotiation and deliberation.

Chapter 4.1 shows that for disaster risk communication to be successful, public perception should be taken into consideration. This involves both a cognitive and affective dimension (understanding and feeling) and is related to trust in protection measurements and mitigation processes. In the process of communication, policymakers should not underestimate the cognitive paradox: a higher trust in protection hampers the preparedness intentions (Terpstra et al., 2009; Lundgren and McMakin, 2013). This relates to the affective dimension, which is influenced by the way risk is communicated. Presenting the same information about risk in different ways, for example mortality versus survival rates, will influence people's perceptions (Slovic, 1993). Unidirectional ways of risk communication can reinforce negative feelings such as fear and powerlessness. In contrast, a two-way, more inclusive communication mode will give citizens the feeling that self-help and solidarity are indeed appreciated by the formal authorities. This communication strategy opens the possibility to build upon both the cognitive and the affective responses in relation to previous experiences with disastrous situations. However, whilst the literature highlights the importance of the non-linear multi-directional approach of communication, research into actual communication practices indicates that a majority still relies on the one-way form of communication (Höppner et al., 2012).

As Chapter 4.2 on decision-making with uncertainty highlights, disaster risk communication takes place through many different communication channels, including face-to-face conversations, telephone calls, group meetings, mass media such as television, instant messaging and interactive social media, in particular Facebook and Twitter. These communication channels, however, are not considered to be neutral. Today's society's social structure, made up of networks powered by information and communications technologies (ICTs) (Castells, 2009), has shaped and influenced decision-making in disaster risk reduction (DRR) and disaster risk management (DRM). Decision-making under uncertainty starts with the question about what the decision-maker knows and where the gaps in the existing knowledge and information are (Ben-Haim, 2006). Consistent with the multi-directional approach to risk communication, recent studies show that for decision-making at times of uncertainty to be successful, a top-down, command and control approach should be abandoned, and should instead involve the public. Formal authorities, in other words, do not have the monopoly in making decisions about the disaster cycle.

The implementation and use of ICTs including social media provide opportunities for engaging citizens in disaster risk communication by both disseminating information to the public and accessing information from them. ICTs have great potential for enabling effectively communicating community-relevant information, in particular in situations in which people are geographically dispersed (Shklovski et al., 2008; Stal, 2013).

Chapter 4.3 on last mile communication builds upon the recent empirical insights on effective early warning systems. The term 'last mile' is understood as a synonym for the immediate affected area and population (Taubenböck et al., 2009). The chapter shows that the impact of the ICT and social media response are influenced by: 1) large-scale power blackouts and the disabling of information and telecommunications networks and 2) the demographics of the disaster including the willingness of people and their organisations to collaborate in sharing, managing and communicating disaster information and their (dis)ability in accessing resources online. Both the vulnerability of the networks and the particularities of the users require innovative solutions.

Adequately designing, implementing and using ICTs are equally important aspects of innovation to make full use of social and technical capacities to improve actual practices in risk communication. Innovation in disaster risk communication is not neutral, but embedded in social and cultural practices. For example, a recent qualitative study assesses the role of age and ethnic and cultural background in the conceptualisation of colour systems used as part of the Heat Health Watch System and the National Severe Weather Warning Service (Tang and Rundblad, 2015).

The final chapter of this part, on innovation and good practices, builds on these ideas and addresses both the technical and the social/cultural dimension of innovation. Communities and evolving decentralised approaches of disaster risk communication are discussed in the context of ICTs development and use. The chapter takes a people-centred approach by focusing on the challenges of communicating with millennials — technologically sophisticated multitaskers (Hartman and McCambridge, 2011) — as an example of how people with specific backgrounds deal with risk communication technologies at times of uncertainty. Finally, it discusses innovations which allow rich media channels to be utilised, including netcentric operations (Boersma et al., 2012) aiming at delivering better targeted actionable risk information to diverse agents across multi-cultural, multi-disciplinary and multi-jurisdictional boundaries.

This Chapter 4 provides scientists, practitioners and policymakers the state-of-the-art knowledge to improve their understanding on communicating disaster risk. It combines insights from psychological, social and computer sciences and presents good practices for those involved in risk communication practices.

4.1 Public perception of risk

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4.1.1 Introduction

As with any scientific domain, the field of risk perception also embraces many subfields and topics. These have been discussed in literature reviews that have sometimes focused on particular hazards, such as seismic hazards (Lindell and Perry, 2000), flood hazards (Kellens et al., 2012), genetically modified foods (Pin and Gutteling, 2008) or multiple hazards (Wachinger et al., 2013; Shreve et al. 2014).

Others have focused on theoretical frameworks such as people's protective action decisions (Mileti and Sorensen, 1990; Lindell and Perry, 2004; 2012), their information seeking (Griffin et al., 2004; Ter Huurne, 2008), how risk is culturally construed (e.g. Steg and Sievers, 2000; Engel et al., 2014) and socially amplified (Kasperson and Kasperson, 1996), or on specific psychological mechanisms such as the role of trust (e.g. Midden and Huijts, 2009; Frewer et al., 2003; Haynes et al, 2008), perceived responsibility (e.g. Mulilis and Duval, 2003; Terpstra and Gutteling, 2008), fear and efficacy beliefs (e.g. Witte, 1994) and cognition and affect (Slovic et al., 2007; Loewenstein et al, 2001).

Understanding how people perceive risks is an important factor contributing to successful risk communication.

Understanding how people perceive risks is one important factor contributing to successful risk communication (e.g. Frewer, 2004; McComas, 2006; Slovic, 2000). However, this chapter is not an attempt to review the risk perception literature. Instead we focus on different approaches in risk communication and illustrate the working of perceptual factors by presenting a number of topical cases. To set the ground, the Chapter 4.1.2 presents different approaches in risk communication. The presented cases comprise capacity building (Chapter 4.1.3), evacuation (Chapter 4.1.4), emergency alerts (Chapter 4.1.5), social media (Chapter 4.1.6) and news media (Chapter 4.1.7). Although some of these chapters focus on certain risks in particular, it is not so much the risk but rather the described socio-psychological processes that are relevant. We conclude with some general remarks (Chapter 4.1.8).

4.1.2 Approaches in risk communication

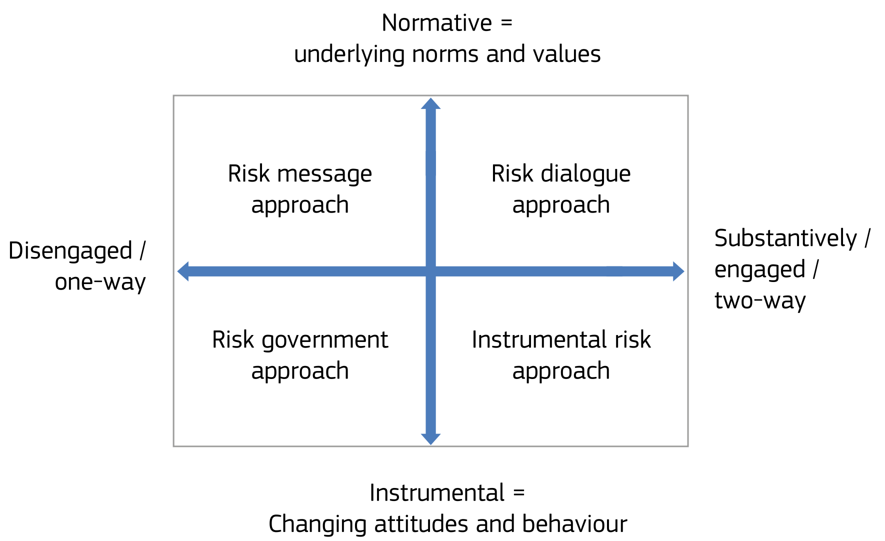
A long tradition in risk communication has relied on the idea that simply informing and educating lay people will increase their understanding and awareness of risk. This one-way information flow from expert to lay is often associated with the so-called deficit model, as experts holding superior knowledge communicate to the less informed.

Many communicative activities are nowadays intending to change behaviour; others are concerned with norms and values. In addition, risk communication can take place in a disengaged (one-way) and in a more engaged (two-way) manner.

For a number of years a broad shift has been taking place throughout Europe (and beyond), characterised by, on the one side, 'a right to know', and on the other side by a stronger focus on 'individual responsibility' of citizens to be prepared for incidents and disasters. As a result, communicative activities that place responsibility for preparedness actions in the hands of citizens are gaining relevance (Wachinger et al., 2013; Walker et al., 2014; Begg et al., 2016). Many are now following a rather instrumentalist rationale intending to change behaviour or attitudes; others are rather concerned with norms and values that underpin, for example, established governance and decision-making structures. At the same time, risk communication can take place in a disengaged, one-way manner as well as in a more engaged, two-way manner (Treurniet et al., 2015). Based on these two dimensions, four approaches of risk communication can be distinguished (based on Demeritt and Nobert, 2014; Wardman, 2008): risk message, risk dialogue, risk government and instrumentalist risk. These approaches can be seen as archetypes suggesting different ways to achieve one's risk communication goals. In practice, examples of risk communication often contain features of multiple approaches (for more details see Kuhlicke et al., 2016).

FIGURE 4.1

Different approaches in risk communication.
Source: Based on Wardman (2008) and Demerit and Nobert (2014)



4.1.2.1 Risk message approach

This type of risk communication is a one-way flow of information concerned with 'transmitting risk information without distortion, bias or misunderstanding' (Demeritt and Nobert, 2014). Fundamentally, this model is based on the idea that responsible organisations are transparent about how they assess risks, what kind of outcomes risk assessments generate and how risks are managed. For instance, by designing risk maps in a way that renders them intuitively understandable, the sender tries to encode the message in such a manner as to increase the likelihood that the receiver will be able to decode the message and draw his or her own conclusion on what to do or not to do (Meyer et al., 2012).

4.1.2.2 Risk dialogue approach

In the risk dialogue approach the distinction between senders and recipients or between certified risk experts and the at-risk lay public is a blur. Exchange forms are based on the assumption that both have a say in the decision-making process. The design of participatory processes depends on its purpose. A common typology is to distinguish between a substantive and an instrumentalist rationale

(Stirling, 2006). The substantive rationale usually aims at increasing the breadth and depth of knowledge that contributes to a decision, as participation allows for the inclusion of tacit or local knowledge that can improve the quality of risk assessments and risk maps, as well as of the management process itself (see Meyer et al., 2012). In the instrumentalist rationale, there is a stronger focus on building trust between actors and on raising awareness and motivation for taking actions to mitigate the impacts of hazards (see Wachinger et al., 2013). The relevance of dialogical forms of communication is also highlighted by many national and European legalisations (Höppner et al., 2010).

4.1.2.3 Risk government approach

Communication within the risk government approach aims at changing attitudes and behaviours, but it does so in a less instrumentalist and explicitly persuasive manner compared to the instrumentalist risk approach. While the latter is opaque about its intention, the government model relies on '… logics of individual choice and self-discipline, rather than explaining new norms of conduct as being imposed from above through coercion' (Demeritt and Nobert, 2014).

In many European countries insurance companies, for instance, offer more affordable insurance premiums if clients voluntarily participate in regular preventive medical check-ups and, by doing so, aim at activating individuals' personal risk awareness and inviting them to consider the negative consequences of smoking or of excessive lifestyle choices; thus creating awareness of their own choices and decisions and the negative consequences these might have on their lives.

4.1.2.4 Instrumentalist risk approach

The instrumentalist risk approach aims at actively changing people's behaviour and pays close attention to the 'interactions between information, attitudes and behaviour' (Demeritt and Nobert, 2014). Due to the increasing prominence of this model, many empirical studies focus on understanding the factors that motivate individuals to take responsibility and action in order to increase their preparedness (Shreve et al., 2014). This type of communication may take many different forms. Quite common are the use of printed booklets or brochures that encourage residents at risk to increase their preparedness. The EU project Tactic has collected a multitude of such examples, which can be accessed through the online platform (TACTIC project, 2017). Also more formalised ways of trying to change people's habits are increasingly established. For instance, in the German state of Saxony citizens are required by law to take precautionary actions to increase their preparedness (Ueberham et al., 2016).

4.1.3 Capacity building through one-way risk communication

The EU Seveso and Floods Directives have made public risk communication an obligatory task of risk management in EU countries. Government websites, dedicated hazard and risk maps and brochures are common methods to inform the general public about risk and possible ways to increase their preparedness. These methods provide information about risks in a non-dialogic fashion and can be seen as examples of the 'risk message approach'. Transmitting risk information without distortion, bias or misunderstanding is a challenge, however, both from a normative and a practical perspective.

From a normative perspective, 'without distortion, bias or misunderstanding' does not mean that the content and tone of the risk communication is 'value free'. Senders of risk messages, either risk experts or policymakers, have their own perceptions of the problem and interests. These are informed by societal norms, political agendas and personal opinions — which are hardly ever universally shared in society. In addition, providing information that is to be understood by many people with different backgrounds often requires focusing on the most 'important' (i.e. certain) aspects and simplification of information. This results in deliberate and chance choices in content (wording and images) and tone, which in turn influences people's perceptions and attitudes in different gradations (also see Chapter 4.1.5).

From a practical perspective, 'transmitting risk information' is hardly ever an objective on its own. A common complementary objective of providing information is to enhance risk awareness and to provide information about individual preparedness actions. This reflects a cross-over between risk message and risk government approaches. The goal is usually to convey a message drafted by a responsible organisation to those who are 'supposed to need' this message in order to be better prepared for disasters.

While such measures have a relatively low cost (Lundgren and McMakin, 2013) and are in many cases essential for getting a certain message across (e.g. warning), non-dialogic risk communication on its own seems limited in its impact on most people's attitudes, active engagement and preparedness behaviour (Moser, 2010). The reason is that changes in attitudes and behaviour are the end result of a complex social-psychological process, and the route to this end result differs greatly between people and communities. Risk communication from authorities will not lead to protective action decision-making unless people receive, heed and comprehend the socially transmitted risk information (Lindell and Perry, 2004). For people to act upon a risk message they must perceive its relevance as well as a sense of urgency. What is relevant or urgent for one person may not be so for others. For instance, changing the battery of a smoke detector may be linked to a personality trait (e.g. high risk aversion or a prevention orientation; e.g. De Boer et al., 2014), previous experience with fire risk, willingness to adhere to a perceived social norm (e.g. "I should have a working smoke detector") or because of practical circumstances (e.g. being a smoker). However, even with these factors present, one may fail to take action. For instance, dealing with risk may arouse negative affect in people, which may in turn result in attempts to control their feelings instead of taking action (e.g. denial), as one may feel unable to perform required actions (low self-efficacy), have little faith in the protective action itself or action is hampered due to practical response barriers (e.g. having other priorities).

There is no such thing as 'one size fits all' in risk communication. Resilient behaviour is more likely when there is a mix of communicative approaches and other types of measures in place. Risk communication is based on a thorough understanding of risk perceptions and capacities that are shaped through the historical and local context.

Evaluations of a campaign about communicating flood risk, organised by the city of Zurich, showed that one-way risk communication can improve flood preparedness to some extent; i.e. home owners' flood awareness and their intentions to implement protective actions did increase (Maidl and Buchecker, 2015).

The majority of respondents felt better informed after the information campaign (only 17 % reported that the campaign did not increase their knowledge) and regression analyses revealed that the perceived usefulness of the material provided had the strongest effects on flood preparedness intentions. A perceived need for information had greater effects on preparedness intentions than risk awareness itself, underlining that the motivation to do something increased through the information campaign. However, since the overall effect of the information campaign was rather low, the authors argued that a single-event campaign is unlikely to have profoundly positive effects on preparedness behaviour and therefore needs to be embedded in a long-term risk communication campaign.

Empirical studies also indicate that it is not so much the information itself that is of relevance but rather the wider context within which such information is communicated. Engel et al. (2014), for instance, focus on the role of disaster subculture as a way to explain how two neighbouring communities have developed different strategies and practices to deal with flood events. These subcultures featured differences in beliefs, knowledge, symbols and preparedness and response patterns. Their findings suggest risk communication would require different approaches in both communities.

Therefore, what is feasible and effective in one context may be difficult or ineffective somewhere else. There is no such thing as 'one size fits all' in risk communication. Resilient behaviour is more likely when there is a mix of communicative approaches and other types of measures in place based on a thorough understanding of risk perceptions and capacities that are shaped through the historical and local context. Finding the right mix of measures is therefore a challenge.

4.1.4 Developing flood evacuation strategies through dialogue

In an attempt to hit the right note in risk communication, this paragraph presents a case study that tested effects of different risk communication storylines on citizens' flood evacuation intentions in the city of Dordrecht (Terpstra and Vreugdenhil, 2015). Dordrecht is located on an island in the Dutch river delta. A potentially dangerous situation occurs when high river discharges result in high water levels that are suddenly further increased by a storm surge pushing sea water into the river delta. Evacuation models indicate that in such a case only between 10-20 % of the population will be able to leave the city before the levees break. When they do, water depths may vary between 2-5 metres and the best chance of survival is to seek shelter in homes on a higher floor or in a high building in the neighbourhood. To reduce the potential number of casualties, the authorities aim to develop and communicate a strategy based on sheltering at home or in a public building.

In 2015 the municipality started a risk dialogue by involving citizens in focus groups to understand their flood perceptions, their evacuation attitudes and their concerns and suggestions. To gain further insight into the level of support for 'staying at home' or 'going to a public shelter', a questionnaire survey was performed. The questions asked were embedded in two different storylines, which reflected two different communication frames that emerged from previously held focus groups. 'Framing' in communication refers to the systematic use of words and symbols reflecting underlying norms and values. For a risk dialogue it is important that people are able to relate to the norms and values and support the frame that is used. Framing can also be regarded as a form of nudging. Nudging refers to '…any aspect of the choice architecture that alters people's behaviour in a predictable way without forbidding any option or significantly changing their economic incentives.' (Thaler, Sunstein, 2009). A more pessimistic 'Self-frame' emphasised that in case of a flood, people are on their own for a few days and food, water and utilities are unavailable and they eventually have to evacuate from the flooded area on their own.

Cognitive (beliefs) and affective (feelings) factors are important predictors of attitudes. These are influenced by the way risk information is framed in communication messages.

The more optimistic 'Together-frame' emphasised the community perspective meaning that people are in it together and will try to help each other, and authorities will assist in evacuation where needed and arrange basic stocks of food, water and utilities in shelters. All respondents (about 625 citizens) answered questions related to their efficacy beliefs, feelings and support for two evacuation options (staying at home, going to a public shelter) and their current evacuation intentions. More questions were asked, but for our purposes we will discuss this subset. On a 1-10 scale, both strategies received higher rates in the Together-frame—i.e. staying at home (Self-frame: 6.2 vs. Together-frame: 6.3) and going to a public shelter (Self-frame: 5.2 vs. Together-frame: 6.0). Remarkable, however, is the fact that both strategies were rejected by a substantial number of respondents: about 27-28 % rejected staying at home while 36-52 % rejected going to a shelter (upper limit % reflects rejection in the Self-frame).

To further explain these results, the authors evaluated respondents' efficacy beliefs and fear-related feelings. Efficacy beliefs reflect the extent to which a person believes a protective action is effective in the protection of people and/or property (e.g. Lindell and Perry, 2004, 2012). Fear-related feelings such as dread is a negative affective state. Affective states influence people's judgements (Loewenstein et al., 2001; Slovic et al., 2007) and can be unlocked by framing information (Terpstra et al., 2014). For instance, Finucane et al. (2000) performed framing experiments to influence perceived risks and benefits of nuclear power, natural gas and food preservatives. Their experiments showed that when information portrayed the benefits as high (or risks as low), the subsequent experience of positive affect caused subjects to perceive risks of nuclear technology as low (or benefits as high). Conversely, when risks were framed as high (or benefits as low), the subsequent experience of negative affect caused subjects to perceive benefits of nuclear technology as low (or risks as high).

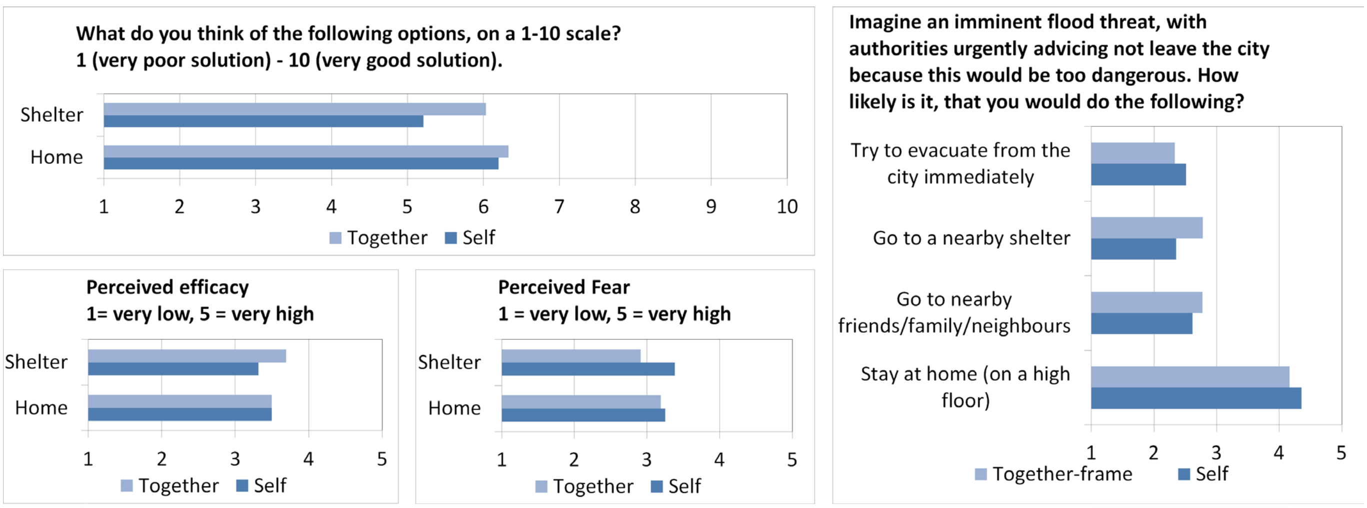
In line with experiments of Finucane et al., additional analyses of the Dutch flood risk data showed that respondents held more favourable attitudes in the more optimistic Together-frame since this frame resulted in lower negative affect/fear and higher efficacy beliefs. Specifically, staying at home received a (marginally) higher score in the Together-frame because it evoked slightly lower levels of negative affect/fear. Going to a public shelter received a higher score in the Together-frame because this frame evoked lower levels of negative affect/fear and higher trust in the efficacy ('being safe') of a public shelter.

Respondents' intentions also revealed an interesting pattern. Staying at home was regarded as likely by about 88 % of the respondents, while going to a nearby shelter or going to family, friends or neighbours was regarded as likely by a substantially smaller number of people (25 % and 28 %, respectively). So even though attitudes towards staying at home and going to a public shelter are similar (at least in the Together-frame), the majority preferred to stay at home. Finally, the fact that 19 % of the respondents considered leaving the city, even though the authorities urge them not to, is remarkable. These people may unnecessarily risk their lives. Their intention to flee the city is correlated with their attitude towards staying at home or going to a public building. That is, respondents who hold less favourable attitudes towards staying at home or going to a shelter are more likely to flee the city in case of an urgent flood threat.

Overall, the meagre level of support for staying at home or going to a public shelter suggests that these strategies can be further detailed. A clear action plan on how citizens are supported prior to a flood (e.g. food and water supply and setup and arrangements in shelters) and afterwards (e.g. a rescue plan) is an important starting point. Based on a further risk dialogue with citizens, experts in flood risk management, utilities, medical and rescue services, it seems that such a plan can be developed. In addition, developing a positive yet realistic storyline for risk

FIGURE 4.2

Perceived fear, efficacy, support and intentions regarding flood evacuation. Source: Terpstra and Vreugdenhil (2015).



communication based on the capacities available in the local communities (e.g. neighbourhoods) can help to gain further support among citizens and reduce chances that people risk their lives by fleeing the city while the levees are about to break.

4.1.5 Facilitating public response through wireless emergency alerts

In the case of an imminent threat, authorities require communication channels that deliver warnings accurately and quickly to a potentially large number of people. A relatively new development is the so-called Wireless Emergency Alerts (WEA). Several countries have started sending out WEA to mobile phones and other devices aiming to alert people at risk and help them to react adequately (Gutteling et al., 2014). As one-way communication tools, WEA are an example of the risk government model. Many of these systems are based on the mobile phone broadcast technology. There is no need to have Wi-Fi or internet or to subscribe to the service. However, technological development and its implementation has outpaced studies on the effectiveness and limitations (Bean et al., 2015). To date, only a few studies have evaluated mobile device-delivered warning messages (Sutton et al., 2014; Terpstra et al, 2012).

A United States report lists several general insights necessary to facilitate adequate public reactions to WEA, among which: (1) effects should be studied after real events, not in hypothetical situations; (2) people need to be trained to properly understand the warning system; (3) the alert needs to attract attention; (4) people seek social confirmation of a warning message before taking protective action; and (5) warnings must contain information that is important to the public (Committee on Public Response, 2013). This chapter describes a recent Dutch study on the public's reactions, which is partly based on these general insights.

In the study people were questioned some time after the implementation of the WEA system in real local emergency situations in three Dutch cities. In the first two cases the emergencies were large fires in non-residential industrial areas with a release of potentially hazardous smoke and soot particles to nearby residential areas. The third situation was a large fire in a historic city centre, causing one casualty. Randomly selected mobile and land-line phone numbers of people living in the broadcast area were dialled by trained agency interviewers, asking whether they had received the WEA. In the Netherlands the WEA system is known as NL-Alert. If they had, some additional questions were asked (e.g. their self-reported behaviour) and people were invited to complete an additional online questionnaire measuring psychological and behavioural determinants derived from conceptual models on risk communication (Witte and Allen, 2000; Floyd et al., 2000; Lindell and Perry, 2012).

These models suggest that receivers of warning messages first assess the threat level, creating some level of personal urgency, and subsequently assess their ability to personally cope with the emergency situation. Coping appraisal is related to one's belief to be able to perform the recommended behaviour and one's belief in the adequacy of the provided advice. When the threat is seen as personally relevant, and the coping appraisal is positive then one will decide to execute the recommended adaptive behaviour. However, when the threat is seen as relevant but coping is seen as impossible, some psychological reframing of the situation (e.g. psychological denial or defensive behavioural avoidance) is a likely reaction. In recent years, studies have shown that in emergency situations the individual is an information seeker but also an information source for others. Existing research suggests that perceived information sufficiency — that is, to which level one is satisfied with one's information position — predicts additional information seeking and information sharing. Also, the perceived quality of the warning message is an important indicator of its effectiveness (Renn and Levine, 1991; Earle, 2010).

Wireless emergency alerts (WEA) are a relatively new method to deliver warnings to a potentially large number of people.

Looking in more detail at the public's reactions to receiving the WEA, some findings are noteworthy. An example of the WEA is this message that was sent to inhabitants:

NL-Alert 20-01-2013 14.50 Setheweg Meppel. Major fire. Keep clear of the smoke!

Close windows and doors. Turn off ventilation. New message follows.

The structure of all Dutch WEAs is similar: sender (NL-Alert date and time), threat (major fire), location (Setheweg Meppel) and advice (*Keep clear of the smoke! Close windows and doors. Turn off ventilation. New message follows*). The respondents' reactions were measured on five-point scales (see Table 4.1).

Overall, the scores indicate that the emergencies had relatively little personal impact for most participants. However, even in these relatively low impact situations, there are some noteworthy findings. On average, respondents valued their coping abilities as relatively high and clearly indicated that the included message components (sender, threat, location and advice) were regarded as clear, complete and reliable (message quality). In addition, respondents did not perceive high expectations to be knowledgeable and responsible with regard to their behaviour in these situations (social norms). In absolute terms, perceived fear and perceived threat were not high, although they were somewhat higher in the Leeuwarden case. This seems reasonable since the Meppel and Oisterwijk fires occurred at some distance from residential areas, while the fire in Leeuwarden took place in the historic city centre. In addition, compared to the Meppel and Oisterwijk cases, respondents from Leeuwarden were somewhat less satisfied with the information received and reported more avoidance (i.e. to continue with what one was doing) and less adaptive behaviour (i.e. to comply with the advice and seek and share information). Two alternative explanations come to mind. First, emergency services in Leeuwarden failed to describe the location of the fire, which may have caused lower levels of satisfaction with the information provided, and they did not mention any personal threat, which resulted in higher disinterest in the situation. Second, higher levels of perceived threat and fear may have caused stronger fear control responses, resulting in more avoidance reactions and less adaptive behaviour. Even though the sample was small and these incidents had relatively little personal impact, correlations did provide some support for these explanations. Adaptive behaviour was predicted by higher perceived fear, seeking social

TABLE 4.1

Mean (standard deviation) for the measured determinants after three WEA cases. Source: Gutteling et al. (2014)

	Case 1 (Meppel)	Case 2 (Oisterwijk)	Case 3 (Leeuwarden)
N=	175	181	287
Self-reported Behaviour			
Adaptive (a)	1.71 (0.26)	1.69 (0.29)	1.55 (0.29)
Avoidance (b)	1.17 (0.38)	1.12 (0.33)	1.46 (0.50)
Perceived social norms (c)	2.37 (1.10)	2.30 (1.03)	2.13 (0.99)
Efficacy beliefs (c)	3.93 (0.93)	3.90 (1.06)	3.97 (1.04)
Perceived threat (c)	2.41 (0.82)	2.59 (0.86)	2.90 (0.82)
Perceived fear (c)	1.72 (0.62)	1.69 (0.57)	2.32 (0.69)
Perceived message quality (c)	4.31 (0.77)	4.37 (0.75)	4.32 (0.81) (e)
Perceived information sufficiency (d)	3.59 (1.11)	3.63 (1.11)	2.98 (0.82)

a. telephone: 1 = none of the adaptive actions taken, 2 = all adaptive actions taken
b. telephone: 1 = no avoidance, 2 = complete avoidance
c. online: 1 = low, 5 = high
d. online: 1 = dissatisfied, 5 = satisfied
e. In Leeuwarden the component 'location' was missing and therefore not evaluated

confirmation and perceived warning quality. Stronger avoidance was predicted by higher levels of perceived risk, fear and higher perceived expectations from one's social environment. Overall, the study presents a favourable impression of the public's evaluation of the WEA system; however, more research is needed with other types of emergency situations to fully understand the psychological, behavioural and communicative reactions of receivers.

4.1.6 Effects of interaction on social media in emergencies

Social media (Twitter, Facebook, blogs, etc.) have been under the attention of risk and disaster managers longer than WEA. Social media and WEA provide similar possibilities to inform the public of imminent emergencies. However, social media also allow for feedback in the form of user-generated content (opinions, observations, etc.) or geospatial information (Palen et al., 2009; Terpstra et al., 2012; Feldman et al., 2016; Houston et al., 2014; Committee on Public Response to Alerts and Warnings using Social Media, 2013; and many others). This chapter aims to describe studies on the effectiveness of social media in emergencies. The use of social media with the objective to influence people's behaviour is therefore an example of the instrumentalist risk approach.

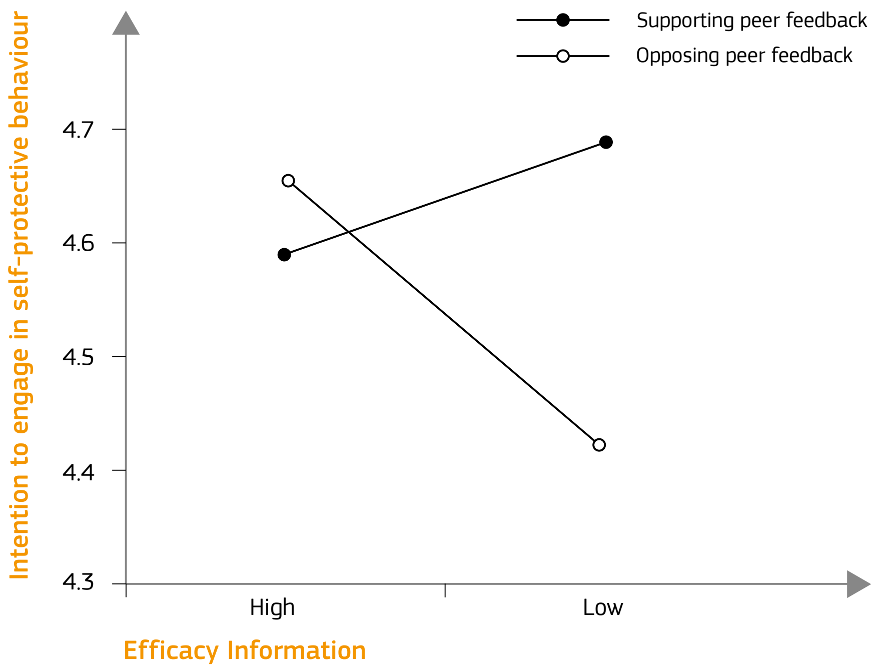
Social media are intensively used in times of crises to share information and support or oppose opinions. A recent study indicates that when official information is regarded as effective, peer feedback is less influential.

As with WEA, there are few empirical studies indicating at a general level what the impact of social media disaster information is or how social media can be designed to be effective disaster-warning tools. The number of studies that have analysed social media messages after real incidents and disasters is steadily growing. A United States study analysing the use of Twitter after a disaster (the Tennessee River dam break) indicated that the amount of information shared by citizens — even those not in the direct vicinity of the emergency location — is considerably greater than the 'official' information from governmental organisations and the company (Sutton, 2010).

Twitter users also tended to be critical toward the official information and corrected wrong information. Starbird and Palen (2010) studied Twitter messages after the Red River flood of 1997 and the the Oklahoma wildfires and found that Twitter messages from those directly involved in the situation

FIGURE 4.3

Interaction effect between efficacy beliefs and peer feedback on the intention to engage in self-protective behaviour.
Source: Verroen et al. (2013)



are retweeted relatively often. Information provided by local news media are also retweeted relatively often. A Dutch study analysed Twitter messages just before, during and immediately after a huge storm which hit a large public open air music event (Terpstra et al, 2012). In the Twitter messages, weather predictions were found as well as rumours and messages that were focusing on providing help after the emergency. When the scale of the emergency became evident, one person took the initiative to organise the inhabitants of a nearby town to provide help (places to spend the night, food and drink, showers, clothing, Wi-Fi, etc.). The data suggested that some of the Good Samaritans were Twitter novices.

An important downside of analysing communication after real events is the difficulty in analysing cause–effect relations of communication messages. This requires communication experiments in a controlled setting where researchers can manipulate perceptual factors by providing different information to separate groups and compare their responses. Although such studies are quite common in communication research, applications to social media are scarce.

Verroen et al. (2013) focused on a typical characteristic of social media communication: people's positive and negative feedback on an earlier distributed message. The message contained emergency information in the context of a high-impact risk, namely the derailment of a freight train carrying a highly flammable and toxic substance. These authors were interested in the interplay of the perceived efficacy of the emergency information and peer feedback, such as responses on social network sites (e.g. Twitter) and the effect of this interplay on the intention to engage in self-protective behaviour.

The study pitted high- and low-efficacy information messages against supporting (positive) and opposing (negative) peer feedback (N =242). Although the study used a hypothetical emergency situation, the participants were selected based on the fact that they lived in an area close to an existing railroad track used by these high-risk trains. Results showed a significant interaction effect between efficacy information in a news article and peer feedback from Twitter messages on both the intention to engage in self-protective behaviour (see Figure 4.2) and the levels of involvement.

Participants who received the news article with more efficacy information were similarly influenced by supporting or opposing peer feedback via Twitter messages.

However, among those who received a low efficacious news article, the effect of peer feedback on these two variables was significantly stronger. Supporting peer feedback (that is peer feedback that supported the advice in the news article) resulted in a significantly higher intention to take protective measures (and involvement) than opposing peer feedback (that is feedback that questioned the advice in the news article). Apparently, when in doubt about how to act to mitigate risk, the tone of peer feedback on social media is important for one's decision making.

4.1.7 Role of news media in defining human responses to crises

In this final case we discuss the role of the news media. This case is not an example of one of the four risk communication approaches in particular. Rather that news media can be regarded as a (highly) influencing factor in each of these approaches, as they reflect on the norms, values and behaviour of people and organisations in relation to risks, incidents and crises. People may be influenced not only by how information about the actual risks is framed, but also by how different frames concerning reactions and behaviours to risks and dangers are put forward in media articles and reports after critical events. The role of media in contributing to erroneous beliefs and myths about human behaviour in stressful situations has been discussed for some decades in the social science literature, culminating in a number of critical analyses of the reporting of reactions to Hurricane Katrina in 2005 (Tierney et al, 2006). More recent work has further demonstrated how subtle and implicit framing can define the portrayal of human reactions, potentially influencing the expectations and evaluations of both the public in general and risk and crisis professionals in particular. In an analysis of media reporting from six different crisis events affecting Swedish society, including natural disasters, antagonistic threats and diffuse threats, Nilsson et al. (2016) identified three dynamic interrelated processes simultaneously at work in framing public reactions.

The first process, that of identification, concerned individuals and groups that were referred to as affected, and in what context. For example, in the natural disaster events, some groups were described as vulnerable and affected by serious losses in terms of economic value of forestry, while others with less tangible losses were barely mentioned. The second process refers to characterisation of how different individuals and groups reacted and coped with the situation. In this process certain characteristics tended to be attributed collectively to groups among the public, creating ingroups and outgroups. This pattern was particularly evident in the case of antagonistic events (one case concerned street shootings in a major city), separating the fear reactions of law-abiding citizens from those of victimised groups with suggested criminal links.

News media reports play a very important role in effective communication and support public needs in stressful situations.

Finally, evaluation processes that provided signals could be identified, sometimes quite subtle, as to which reactions and behaviours could be considered as expected, accepted or stigmatised. For example, the choice of certain words or references could suggest that individuals are either reacting logically, are not reacting sufficiently responsibly or are overreacting. Such suggestions indirectly communicate expectations and evaluations of correct or incorrect behaviour. Thus, for example in the case of the influenza A (H1N1) pandemic and the issue of vaccination, quite subtle semantics could reflect evaluations of who reacted sensibly (and got vaccinated) and who did not. Interestingly, these evaluations were somewhat reversed when cases of narcolepsy were linked to the vaccination campaign, leading to a new and somewhat different media debate (Scott and Enander, 2016). Taken together, these findings demonstrate a need to examine critically frames which may distort a realistic view of public needs and reactions when faced with risks, thus leading to ineffective communication and support.

4.1.8 Conclusions and key messages

In this chapter we presented different approaches to risk communication and acceptance of risk communication and addressed a number of socio-psychological concepts that have been shown to influence people's perceptions, attitudes and behaviour in the face of a wide variety of risks. Based on the pillars of the Disaster Risk Management Knowledge Centre, we conclude with the following three key messages.

Partnership

For a number of years now, a broad shift has been taking place throughout Europe (and beyond), characterised on one side by 'a right to know' and on the other side by a stronger focus on 'individual responsibility' of citizens to be prepared for incidents and disasters. Risk communication that is based on one-way media campaigns alone, telling people how to prepare, is hardly effective. In terms of partnerships, engaging in a dialogue with local communities to understand the historical and local contexts is an important basis for future risk communication that focuses on stimulating resilient behaviour.

Knowledge

Sound knowledge of the effects of communication messages based on communication experiments and tests is indispensable for delivering effective communication. In addition, there are many best practices available that have been identified by EU projects, such as Tactic and CapHazNet, that may offer inspiration.

Innovation

In some cases a more fundamental approach may be needed to set up and monitor communication effects and improve communication practice. This is especially important where it concerns innovative methods such as the use of new communication tools (e.g. WEA), complex topics (e.g. flood evacuation strategies), activities that cause great societal unrest (e.g. CO2 storage) or where norms and values are at stake (e.g. stigmatisation in media reports). In such cases, profound insight from communication research can be useful to support further decision-making.

4.2 Decision-making under uncertainty

Tina Comes, *Anouck Adrot, Caroline Rizza*

4.2.1 Technology innovation: promise and reality for decision-makers

For more than a decade now, information has been recognised as a form of aid (IFRC, 2005). Uncertainty has been largely related to the lack of predictability of some major events or stakes, or a lack of data (Argote, 1982). To overcome this uncertainty, the traditional decision support paradigms suggest collecting more information. Therefore, decision-makers have focused on gathering and analysing more and more data about potentially disaster-affected areas (Comfort, 2007; Wybo and Lonka, 2003).

In parallel, progress in engineering continues to promise connectivity, broader bandwidth and unknown computational power to all (Gao et al., 2011; Meier, 2014). The use of social media that first gained prominence in the 2010 Haiti earthquake has become 'main stream' in the response to Typhoon Haiyan in 2013 (Butler, 2013). Technology-driven data sources such as GPSs, radio frequency-based identification tracking, remote sensing, satellite imagery or drones enable real-time monitoring (Comes and Van de Walle, 2016). Biometric identification technologies are increasingly used as tools for refugee management (Jacobsen, 2015) and relief provision shifts towards virtual distributions through digital payment systems or 'mobile money' (Sandvik et al., 2014). However, the more decision-making depends on (big) data the more challenging it becomes to manage and analyse:

- In a fragmented and 'post-factual' society, information coming from heterogeneous sources and actors is likely to be contradictory — and recent elections, from Brexit to the United States in 2016, highlight that (mis-)information becomes a commodity which is a source of influence and power.
- Volatility — the pace of change in data and public opinion is unprecedented, drastically reducing the time available for strategic policy decisions (Noveck, 2015).
- Because of the ever-more complex socio-technical interdependencies, the implications of decisions cannot be clearly assessed any more (Comes et al., 2011).

Technology has enabled new forms of data collection and participation. It has introduced a new layer of complexity in decision- and policymaking. Technologies are enabling but never the end-solution.

Besides a lack of information, uncertainty can also stem from a lack of understanding of the actual information (as opposed to rumours) and the impact of a decision on complex systems; as a result, decision-makers are not even aware of what is uncertain (Taleb, 2007). From this perspective, some authors have strongly advocated a renewed perspective of decision-making strategies (Makridakis and Taleb, 2009). The need for new participatory approaches to making decisions in the Big data era has been equally recognised by the European Commission under the Citizen Science theme (EC, 2013) as well as central humanitarian actors such as the International Federation of Red Cross and Red Crescent Societies with its 2013 World Disasters Report, which explicitly focused on technology and the future of humanitarian action (IFRC, 2013), and a series of reports by the United Nations Office for the Coordination of Humanitarian Affairs, Humanitarianism in the Network Age (OCHA ,2012), and the implications of Big data (Whipkey and Verity, 2015).

The uncertainties related to this new decision space will be unpacked in this subchapter. Since decision-making under uncertainty is important in crisis and disaster risk management, this chapter covers both domains, making distinctions whenever necessary.

We first discuss in Chapter 4.2.2 the standard paradigms of rational choice, emphasising new types of uncertainty that decision-makers are confronted with; this view entails that power relations are an important driver of uncertainty. We discuss power as a hidden dimension, introducing behavioural uncertainty in Chapter 4.2.3. Power relations can also introduce legal and ethical dilemmas, particularly when it is about collecting, analysing and sharing uncertain information by using technology; such dilemmas are reviewed in Chapter 4.2.4. We conclude with a taxonomy of decision approaches and processes to manage uncertainty in Chapter 4.2.5 as well as a discussion and recommendations for science and policymaking.

4.2.2 Uncertainty undermining the paradigm of rational choice

The standard paradigm of decision-making under uncertainty suggests that uncertainties are due to inherent randomness in an event, such as throwing a coin. Such uncertainties can be best captured by probabilities. To this end, scientists or citizens collect and evaluate data, which are translated into a model. For instance, the chances of a flood, storm or earthquake affecting a community is typically given by the frequency of the occurrence of such events over a certain period, for example a 100-year flood. Data to predict such a flood include rainfall or changes in temperature upstream. Standard decision support tools assume that a crisis evolves from a chaotic beginning into a steady state that follows patterns which can be identified. Therefore it is sufficient to collect comparable data to retrieve the patterns.

However, this implies that data are comparable and standardised and were collected following a series of specific methods. Applying expected utility theory (French et al., 2009), i.e. recommending the decision that leads to the highest expected value, also means that the recommendations lead to the best outcome over a series of (repeated, similar) events.

Disater risk management deals with highly uncertain situations. Such uncertainties can be best captured with probabilistic approaches. Decision-making under uncertainty requires the understanding of the underlying uncertainties and assumptions within the probabilistic models or the data.

In addition, the variety of the data collected and analysed today ranges from sensor measurements to social media information or radio conversations (Comes, 2011). Each of these types of data is fraught with different types of uncertainty or error: while sensors can malfunction or fail, human judgement is typically ambiguous, subjective and highly contextualised (Palen et al., 2010). As such, new approaches that help policymakers consolidate the different types of uncertainty inherent to the heterogeneous data need to be developed.

In addition, the potential impact of a flood, for instance in terms of damage to infrastructure, is much harder to predict than the event itself. Behavioural issues need to be considered; for example where will people turn for help and how will they support each other? The use of smart phones in the refugee crisis, allowing refugees to navigate their way across European borders, for instance, has caught many organisations and governments by surprise (Comes and Van der Walle, 2015).

Despite these complexities, under the time pressure of (looming) disasters and crises, often simple and straightforward recommendations are sought for their ease of communication (Renn, 2008). Since disasters are low-probability events, however, such models can be misleading, particularly if there is 'blind trust' in a prediction or model (French and Niculae, 2005) — and no room to reflect upon the underlying uncertainties and assumptions within the model or the data.

4.2.3 Decision-making contexts and new sources of uncertainty

Three major contexts for decision-making in disaster risk reduction have emerged with the push for increasing digitalization. Creating information does not require specific education and background any more. By relying on open software tools anyone can create a map, dashboard or analysis, opening opportunities for participation and engagement.

- Participatory and community-based approaches emphasise novel possibilities of engagement and can empower local communities through joint planning and crowdsourcing (Edwards, 2009; Norris et al., 2008). An example is a citizen science approach to flood protection, where communities themselves were involved in research from scratch and were thus better informed in decision-making (Wehn et al., 2015). Uncertainty here is related to the fragmentation of voices, the subjectivity of data and the volatility of public opinions:

- Increasing automation and dominance of technology-driven approaches refer to the integration of information into decision practices through pervasive information technology (IT). Using satellite imagery, drones and artificial intelligence for damage assessment after an earthquake or a forest fire is just one of many examples. While data-driven approaches sometimes suggest the increase in objectivity, they are often far from complete and digital shades persist. For instance, social media analyses that rely exclusively on Twitter neglect the fact that Twitter users are hardly a representative sample of the population. At the same time, commercial proprietary algorithms and software (such as those used by big search machines like Google and Facebook) are certainly not neutral, and uncertainty persists about how data are analysed.

- Virtual collaborations in networks of experts and volunteers include, for instance, 'crisis mappers' that help local communities map out assets such as hospitals or schools. The use of local implementing partners, combined with virtual elements, has led to increasing centralised coordination and remote management, particularly when access is difficult (McDonald, 2016; Comes and Van de Walle, 2015). Uncertainty stems from the fact that decisions are made removed from the context. A mapper in Oslo or Brussels may not know what is most important to fight fires in Greece or Portugal. Decisions and policies designed in capitals are often political in nature. They are related to power structures, negotiations and standards that neglect the specifics of local context. New movements such as the Global Parliament of Mayors (n.d.) argue that because of such uncertainties, even strategic and policy decisions must be made at city (or local) level.

Expertise is not limited to policy-makers and scientists any more. Decision-making under uncertainty needs to respect new contexts, environments and shifted power structures.

To deal with these emerging decision-making contexts, policymakers, responders and scientists are expected to abide by given professional standards and norms such as emergency plans, risk management and resilience frameworks and good academic practice. Maybe most prominent are the humanitarian principles, which include humanity, impartiality, neutrality and independence (OCHA, 2010). However, through readily available software, new grassroots initiatives and volunteers that do not subscribe to any standard or code of conduct can produce the same types of information products, maps or analysis — without quality assurance. For instance, the easy use of Ushahidi or Google Maps contributes to the coexistence of similar maps with conflicting information, which can aggravate uncertainty. Moreover, algorithms that structure data collection and analysis underlying these products are often proprietary and not transparent. Having lost the exclusivity to create information, scientists should therefore ensure that their approach to data collection and modelling is transparent and matches the purpose of the specific situation and context. At the same time, uncertainty related to professional products that are designed to support decisions leave way for interpretation and 'spinning' of any information into a favourable direction, introducing motivational biases (Montibeller and von Winterfeldt, 2015). One important aspect of such decisions are power relations between actors and organisations.

4.2.4 Decision-making under uncertainty as a power relation

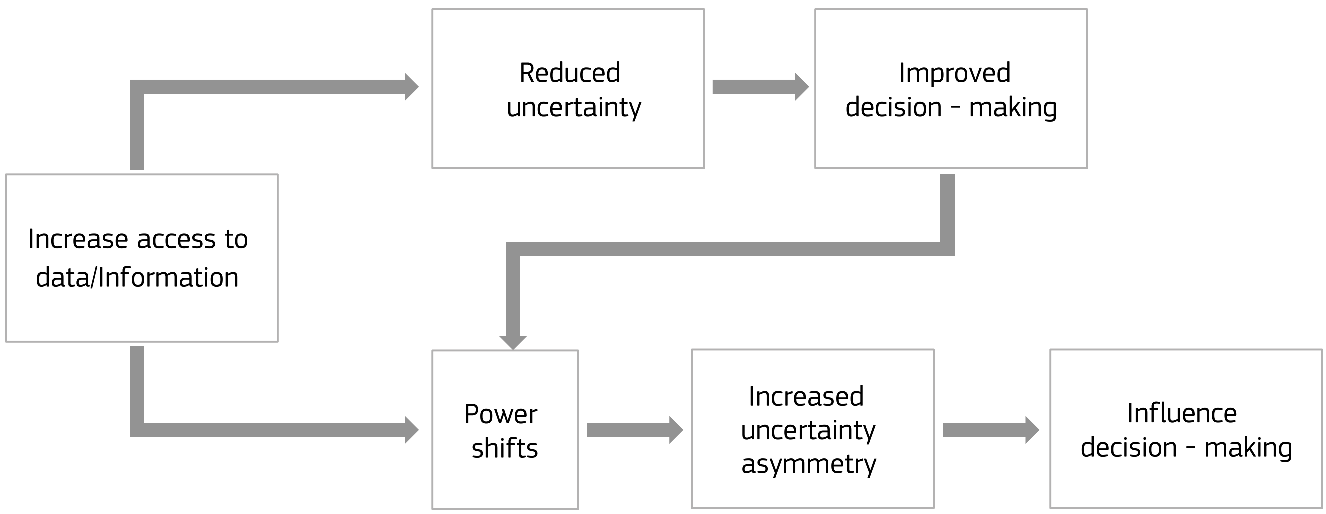
Uncertainty, information and power are intricately related concepts. As outlined in the previous chapter, decision-makers and scientists need to revise standards and practices that have emerged with increased information access. Likewise, decision-makers need to fully consider power dynamics in their approach to uncertainty and adapt their practices.

In practice, power can be defined as the extent to which an entity can guide or frame another entity's actions. Entities can be individuals, groups, organisations (companies, non-profit organisations, communities, governments, etc.) and groups of organisations (consortia, alliances, partnerships, networks, etc.). Power is thus key to understanding how collective action emerges and evolves (Prus, 1999).

Power fuels on 'an intent or capacity on the part of one person or one group to influence, control, dominate, persuade, manipulate or otherwise affect the behaviour, experience or situations of some target' (Prus, 1995, cited by Hall, 1997). Information and knowledge are essential to power: to influence, control, dominate, persuade and manipulate others, one needs to know more (Crozier and Friedberg, 1977). Thus, one can strive to maintain asymmetrical levels of information access and uncertainty to

FIGURE 4.4

Power, information access, decision-making with uncertainty
Source: courtesy of authors



gain power over the others. Reciprocally, power shifts affect the level of uncertainty that concern the various actors involved in disaster risk.

Power is a driver of information creation and sharing, which biases seemingly objective data adding a layer of uncertainty to decision-making.

Various cases illustrate how disastrous the effect of power on uncertainty can be. In the aftermath of 2008 Cyclone Nargis, the Burmese junta feared losing its power because of the arrival of foreign aid. It significantly retained information by imposing a media ban. By struggling to control information, the Burmese junta prevented the relief actors from collecting information. Uncertainty about humanitarian needs increased at the expense of the population (Pan et al., 2012).

Criticism arose and was directed towards the overwhelming power of the international humanitarian apparatus in the aftermath of the 2010 Haiti earthquake. The government's infrastructures collapsed and international non-governmental organisations (NGOs) quickly took over, centralising information and allocating resources without sharing information. The local government remained blinded by uncertainty and compelled to rely extensively on international aid. Such asymmetry led to a vicious circle: priorities shifted to the import of western governance standards, which impeded the country's response to the 2010 outbreak of cholera (Biquet, 2013).

While thus being an important driver of uncertainty in decisions (Hart, 1993), power is often mixed up with the surrounding notions (Comfort, 2007). This is, at least in part, because the impact of power is hard to capture. Power relations can shift quickly through interactions and in changing circumstances (Hall, 1997). In addition, power is invisible and 'silent' (Brown et al., 2010) and cannot be bound to a single event, fact or process.

To address this issue, decision-makers need to be aware of uncertainty and information asymmetry in disaster risk. First, decision-makers should understand the implications of a lack of power on uncertainty (Chapter 4.2.4.1). Second, they ought to identify benefits from genuine information collection (Chapter 4.2.4.2.). Finally, they should consider the implications of information on uncertainty and power in a holistic way (Chapter 4.2.4.3. and 4.2.4.4.). Figure 4.4 provides a representation of how power and information affect decisions.

4.2.4.1 Power as a necessary but insufficient condition to reduce uncertainty

Because power affects communication and coordination patterns, a structural lack of power confronts decision-makers with extreme uncertainty when disaster strikes. Baumgartner and co-authors (cited by Hall 1997) highlight how power influences communication: when an incident strikes, access to information within a group of individuals depends on the underlying power relations. The most powerful actors can radically restrict the number of actors involved in making the decision (Smart and Vertinsky, 1977). The humanitarian example of the 2010 Haiti earthquake illustrates how a lack of power results in high uncertainty and low participation when it comes to decision-making.

To nuance this point, one needs to remember that power, while increasing centrality in decision-making, does not suffice to reduce uncertainty. The 1962 Cuban Missile Crisis vividly illustrates this assertion: powerful actors can centralise information to legitimately influence decision-making in spite of intense uncertainty (Guttieri et al., 1995).

4.2.4.2 Reliable information from other entities an entity can reduce uncertainty and establish power

From an operational perspective, organisations expect information access to reduce uncertainty and support insightful decision-making. The reliability of the decisions made can then significantly influence performance, thereby increasing decision-makers' power in the longer term. Note that 'good' decisions are mandatory; massive data collection alone does not increase a decision-maker's power.
For example, during the 2003 European heat wave, some French hospital

directors relied on their friendships to collect information about potential incidents in emergency rooms. By doing so, they got reliable alerts from the hospitals and triggered and communicated emergency plans quickly enough to capture and mobilise physicians, nurses and other hospital personnel. In the aftermath of the crisis, experts applauded this initiative as well as the hospitals' reliability, thereby supporting the directors' long-term power and legitimacy within the French healthcare system (Adrot, 2010).

4.2.4.3 Information sharing reduces uncertainty asymmetry, thereby rebalancing power relationships and redefining decision-making constraints and modalities

Traditionally, command chains mobilise operational actors to collect information to reduce uncertainty and make decisions. However, information sharing is hardly reciprocal, and typically reporting chains are directed 'upwards' to centralised coordination structures (Turoff et al., 2004). In addition, internet and electricity blackouts and limited coverage can make local communities suffer from restricted access to information and intense uncertainty. In such settings, these local communities often rely on their direct perception, experience and networks instead of professional responders or official information (Comes et al., 2015a). Interestingly, power relations between local and global communities can shift because of technological progress: increased use of smartphones, increased connectivity and open-source tools can catalyse access to data and information. Such access means that additional actors, such as virtual communities, can provide information and participate in operations and reduce uncertainty. For example, the opening of satellite views, through open-source platforms and communities (such as Open Street Map in the aftermath of the 2010 Haiti earthquake or even earlier in the aftermath of Hurricane Katrina), can compel actors with strong supremacy to admit the empowerment of local communities. In addition, the visibility of the virtual citizen community is improved (Palen et al., 2010). In the longer term, such visibility will strengthen these communities' participation in decision-making.

4.2.4.4 A holistic approach to power highlights bigger challenges related to decision-making and uncertainty

Even though information access can contribute to increasing one's power at the response stage, one should keep the side effects in mind. From an institutional perspective, increased competition for information to gain power can result in opportunistic or fuzzy behaviour with respect to information. This, in turn, can negatively affect relationships between local or other professional actors at the expense of the population that has potentially been affected by a disaster. For instance, during the 9/11 response, a large spectrum of actors (citizens and local non-profit organisations in search of institutional visibility) urged on the crisis response stage, providing non-exploitable data and creating confusion, which slowed coordination down (Dawes et al., 2004).

In addition, NGOs can tend to exploit information as an opportunity to gain legitimacy and visibility. Such a tendency is not new. In 1994 Eng and Parker observed how local Mississippi communities shifted their efforts from social interactions to developing legitimacy towards their partners. However, we believe that digitisation can potentially lead to an opportunistic use of information and we therefore call scholars and practitioners to consider the ethical and legal implications of technology-based decisions as a burning issue.

4.2.5 The ethical and legal implications of technology-based decisions

The power implications and uncertainties related to technology require a critical review of the ethical, legal and social issues (ELSI). For instance, how to engage with citizens through social media or how to share information between different agencies and information systems in line with data protection laws remains a current issue. Consequently, designing and developing technologies and practices which address such issues becomes essential.

4.2.5.1 Pandora's Box? Uncertainty related to unintended consequences of informationalisation

We have previously highlighted that behavioural issues, particularly when reinforced by social media platforms, increase complexity and uncertainty in decision-making. Rather than relying on compliance of the population ('keep calm and carry on'), citizen and volunteer groups today emerge and organise, leading to 'unintended consequences'.

Specifically, the case of the 2011 Vancouver riots (Rizza et al., 2014) highlights risks associated with citizen engagement crises through social media. The Vancouver Police Department asked Vancouverites to send their material and to help identify rioters. Feeling empowered by local authorities, citizens started a real manhunt, and some families had to leave the city. This case has pointed out: 1) the 'institutional unpreparedness' in dealing with a huge quantity of data, their quality and the new processes of inquiry they require; 2) the 'unintended do-it-yourself justice', i.e. the shift from supporting crisis managers to vigilantes when citizens overruled authorities and enforced justice on their own terms; 3) the 'unintended do-it-yourself society' supported by the potential of social media for prompting people to act. What happened in Vancouver challenged human rights and values such as fairness, justice, integrity, responsibility and accountability.

For the 2010 Eyjafjallajökull volcano eruptions, Watson and Finn (2014) discussed some of the privacy and ethical implications surrounding the use of social media. Social media allowed persons stranded in Europe to communicate, organise their travel, etc. as well as allowing the aviation industry to get information from its customers. At the same time, social media use led to privacy infringements and inequality. Indeed, over-focusing on social media could lead disaster risk managers to focus on those who produce a lot of data and, consequently, to down-prioritise those unequipped (for example foreign passengers) or unable to use ICTs (for example the elderly). Lastly, 'self-help' between citizens under the umbrella of resilience (i.e. a spontaneous peer-to-peer communication) should not become a way for corporate or public entities to neglect care responsibilities for those who have been impacted by a disaster.

Ethical and legal considerations have become essential in designing and developing technologies and practices which collect, analyse and communicate (uncertain) information and data.

Consequently, designers and practitioners in disaster risk need to consider the uncertainty related to unintended consequences of IT. This implies noticing, anticipating and knowing them.

4.2.5.2 Data protection and privacy concerns: how much uncertainty is needed?

Rizza, Büscher and Watson (2017, forthcoming) underline that (personal) data and information (sharing) constitute the core interest of ELSI concerns in the Big Data era, which makes mass surveillance possible. The collection and processing of data coming from different applications makes the boundary between decision support and control or surveillance fuzzy. For instance, the knowledge database created through such a monitoring system could reveal individuals' habits, routines or decisions and, consequently, infringes citizens' privacy. Big data has even been said to contribute to trapping particularly vulnerable populations in poverty by obstructing the possibility to get loans or access to good education (Waddell 2016). As such, the statistical likelihood that someone from a specific neighbourhood may not pay back a loan blocks individual opportunities. The collection and processing of personal data is also problematic because in crises it can erode basic rights such as freedoms of speech, associations and movement.

To balance the need to reduce uncertainty and collect data with ethical responsibility in scientific and technological developments, an ethic of co-responsibility should emerge (Schomberg, 2013). Research around ELSI aspects of IT also reveals opportunities: integrating IT into disaster risk management with an explicit commitment to ELSI considerations will provide useful insights for a proactive approach to innovation (op. cit.).

Initiatives like 'privacy by design' or 'ethics by design' (European Commission, 2010) attempt to deal with current critiques of the lack of concern for ELSI in the development of new technologies (Rizza et al., 2011). Privacy impact assessments can ensure that technology for disaster risk reduction is developed to protect the interests of end users and stakeholders within the organisational and legal frameworks.

4.2.6 Decision-making under uncertainty: better than muddling through?

The context of decision- and policymaking has become complex. The very nature of the different uncertainties we discussed makes it largely impossible to use probabilities: the socio-technical uncertainties in disaster risk reduction are deep (Comes et al., 2013; Comes et al., 2011; Pruyt and Kwakkel, 2014). Already in the 1950s, Lindblom (1959) had described that decision-makers confronted with such uncertainty are 'muddling through'.

Participatory approaches to model design and scenario analysis have been advocated as a way ahead when the communities affected are clearly known (Comes et al., 2015b; Wright and Goodwin, 2009). Examples range from scenarios for water and flood management (Haasnoot et al. 2011) to urban planning and resource management (Vervoort et al., 2010), approaches that rely on connecting communities and policymakers in the preparedness phase. Scenarios are built in deliberative processes that capture expert knowledge, preferences and values of stakeholders (Kok et al., 2006; Vervoort et al., 2010). While those scenarios serve to establish plans and evaluate alternatives based on a common understanding, they are time consuming to update and adapt to new circumstances or information. As such, they are most useful in the preparedness phase, not in the least to help build networks and partnerships of trust (Comes, 2016b).

The opposing trend relies on artificial intelligence and data mining approaches that enable real-time analysis of data streams to be made. Automated algorithms and tools can be used to extract and illustrate large-scale patterns and trends in human behaviour, damage assessments and communication flows (Meier, 2014; Monaghan and Lycett, 2013; Whipkey and Verity, 2015). As such, they promise fast answers, which is particularly relevant in the heat of a response. It is, however, necessary to ask how such analyses influence human sense-making or possibly introduce biases (Wright and Goodwin, 2009). Particularly if analyses are run remotely and disconnected from the community, there is a series of typical errors that may mislead analyses or the interpretation of results (Comes, 2016a). In addition, the reliance on software, data and algorithms has been increasingly criticised for the lack of transparency and control that communities have over their own data (McDonald, 2016; Sandvik, 2013).

In between there is a large spectrum of semi-automated data collection efforts, semi-automated analyses and assessments that are run by scientists, policymakers from municipality to international level and an increasing amount of local and digital volunteers. With the global availability of technology, software and data, the creation of information products has been democratised. While in the past the design of a map or a dashboard required dedicated technical skills, today anyone can produce graphs, figures and maps. Examples of such volunteer efforts range from the response to Typhoon Haiyan in the Philippines in 2013 (Comes et al., 2015a; Westrope et al., 2014), the Ebola response (Landgren 2015) and the response to the refugee crisis in Europe in 2015 (Comes and Van de Walle, 2015; Talhouk et al., 2016).

Decision-making should reflect the specific context, constraints, needs and stakeholders associated to a decision, including the specific phase of the disaster risk management cycle.

Decisions differ in terms of information required, time scales, geographical scope and actors. The question, for instance, of where to set up a hospital has very different characteristics from general resource-allocation decisions. Both decisions are important but have very different requirements in terms of information granularity, timeliness and updates. Addressing specific decision-makers needs or problems in the socio-technical context is, however, still not commonplace. We propose a decision-centric paradigm for information collection, processing and visualisation that focuses on specific information needs.

4.2.7 Conclusions and key messages

Partnership

Together, scientists, policymakers and communities need to agree on standards that reflect good processes and representations of uncertainties. Citizen science can be a way ahead to providing necessary training and education. In particular, we propose that cultural, social and professional specificities must be thoroughly taken into account in the settling of standards. Since information is always also a source of power, it is imperative to follow the principle of reciprocity — empowering the people who provide information to use it for their own good and strictly following the principles of responsible data and technology.

Knowledge

Given that no single paradigm predominates how decision- and policymakers use information, data and uncertainties drive power relations and introduce ethical and legal dilemmas. So far, standard analyses use, at best, probabilistic approaches to represent uncertainties, neglecting the socio-technical dimension of decision-making, problems of data gaps and consent. The reflections on uncertainties presented in this chapter draw from both practical experiences and theory. They are, however, not readily translated into concrete policy measures or decisions because there is first a need for innovation in science and policy.

Innovation

Researchers need to frame the problem they are studying, including the context and the purpose of a model, simulation or analysis. Assumptions and limitations need to be reflected in the design of decision support systems. When situations are complex and uncertain there is a tendency to simplify the problem and to exert control through limited consultations and conflict avoidance. However, models and recommendations must not oversimplify complex problems, which is a challenge given the call for ‘easily understandable’ solutions.

In addition, we call for the development of methods and approaches that consider the different types of uncertainty from operational decision-making to strategic policymaking. So far, there is no clear understanding of the processes, models and tools that enable institutions to use operational and real-time information to collaborate with citizens to manage disaster risk.

Besides the uncertainty inherent in the new data environment, uncertainty is also rooted in the role of power in decision-making and the lack of addressing the ethical and legal stakes caused by information use. We therefore advocate further research on the socio-technical dimension of uncertainty in decision-making by putting technical, social, organisational, ethical and legal dimensions of information into perspective.

Problems in disaster risk reduction are complex. As such, any model will necessarily reflect this complexity by various layers and levels of uncertainty that will need to be considered in the decision-making process. This means that deliberation processes and communication with stakeholders need to be carefully designed to reflect such uncertainties, even if there is a temptation to go with quick fixes or easy solutions. Error bars or margins of error should not be just a footnote, but rather should be openly discussed. In particular, critical tipping points need to be flagged, such as flood levels that cause a breach in a levee or top wind speeds that damage major infrastructures.

New participatory processes such as risk mapping are increasingly important. In the preparedness phase, they make it possible to establish networks and partnerships that people can rely on during the response. If such processes are also to work effectively in disaster response, decisions, processes and organisational structures need to be adapted to enable the uptake of information provided by communities. Such approaches can only work successfully, if connections are established prior to disasters.

Participatory processes and new governance structures should empower local communities in guiding disaster risk management and reducing uncertainty. However, this implies collective awareness of how power shapes decision-making. Power is a system-wide dynamic that can impact uncertainty for all.

4.3 Last mile communication

***Irina Stanciugelu**, Aurel Bilanici, Ian Cameron*

4.3.1 Introduction: disaster risk management and information and communications technology

Disaster risk management (DRM) is undergoing noteworthy changes, reflecting the emergence of a globalised system of DRM with technological, organisational, and institutional capacities enhancing DRM's ability as a unit in near real time across the globe (Jensen et al., 2015).

ICT is enabling better communications, remote sensing, monitoring networks, warning systems and modelling and geospatial technologies. Various ICT tools such as geographic information systems (GIS) and global positioning systems (GPS) can allow organisations to receive satellite information and produce accurate location information about the affected areas, which can be further linked with socioeconomic, demographic and needs assessment information (Hu and Kapucu, 2014). There are diverse emergency management information systems such as E-Team, Web EOC, SharePoint that make it easier to gather, process and disseminate information, which helps emergency managers make informed decisions (Carver and Turoff, 2007).

Incident management systems can inform disaster response teams with real-time information about the incident and available resources and can help emergency management organisations coordinate efforts (Iannella and Henricksen, 2007). Innovative means, such as citizen observatories enabled by ICTs (e.g. sensor technologies and social media), have the potential to provide new ways of participation (When et al., 2015) whilst at the same time generating relevant information and promoting demand-driven policy responses (Holden, 2006; Rojas-Caldenas and Corona Zambrano, 2008).

Despite the significant advantages of ICT, unequal ICT adoption within and between countries becomes a DRM limitation. As an example, the uneven distribution of warnings in the 2004 Indian Ocean tsunami resulted in many thousands of avoidable deaths.

Various ICTs are used in disaster risk management to help organisations process and share real-time information. Other functions of ICT are to establish different communication channels, to engage with stakeholders and to coordinate among a large number of agencies.

During Hurricane Katrina in 2005 the inadequate monitoring of infrastructure and failed warning systems led to hundreds of avoidable deaths. Also, the different level of adoption of ICT tends to affect the more vulnerable populations disproportionately. More generally referred to as the 'digital divide,' this tends to exacerbate economic differences (Jensen et al., 2015).

In this chapter, we focus on the main changes that ICT brings in DRM. The next chatper present what constitutes an effective early warning system (EWS) (Chapter 4.3.2 and 4.3.3) and investigate requirements for and recommendations on community linkages and community empowerment within the chain of an EWS (Chapter 4.3.4 and 4.3.5). Chapter 4.3.6 and 4.3.7 present the opportunities that ICT technologies and social media provide for engaging citizens in the emergency management and how the new digital technologies could be used to close the last mile communication gap. We conclude with some general remarks (Chapter 4.3.8).

4.3.2 'Last mile' communication and development of early warning systems (EWS)

The notion of the 'last mile' has been popularised in countries of the Indian Ocean in relation to tsunami EWS development (Thomalla and Larsen, 2010). Even so, 'last mile' has been understood differently: 'last mile' as a challenge for rural communities to access media and address this by supplementing traditional media channels for warning dissemination with additional technologies (LIRNE Asia, 2008); 'last mile' as the capacity of the community to take action in response to a received warning and that supports the development of the capacities of local institutions (Singh Bedi, 2006).

Early warning systems are designed to analyse the risks of vulnerable communities, carry out the task of monitoring environmental variables, issue warnings and ensure that appropriate response capabilities are in place.

The Hyogo Framework for Action 2005-2015, which was adopted at the 2005 World Conference on Disaster Risk Reduction, recognises early warning as an effective tool to reduce vulnerabilities, save lives and help protect livelihoods as well as to improve preparedness and response to natural hazards.

The Hyogo framework takes on the perspective of the 'last mile' in stressing that disaster risk reduction (DRR) must be 'underpinned by a more proactive approach to informing, motivating and involving people in all aspects of DRR in their own local communities' through multi-stakeholder and cross-sectoral partnerships (UN/ISDR, 2005). The diversity in interpretations of the notion of 'last mile' hints at the complexities associated with the links between DRM and ICT, the development of national and regional EWSs and the advent of social media in crisis management.

Early warning is defined as 'the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response' (UNISDR, 2004). EWS defines a technological infrastructure that can assist in carrying out these tasks. However, the EWS needs to go beyond this infrastructure by taking account of how risks are understood and providing information for warning messages (Horita et al., 2016). EWS has four interlocking elements (Grasso, 2012):

- risk knowledge — to understand the risks (hazards and vulnerabilities) and priorities at a given level;
- monitoring — to stay up to date on how the risks and vulnerabilities change through time;
- response capability — so that each level (pre-season mitigation activities, evacuation or duck-and-cover reflexes) is able to reduce risk once trends are spotted and announced;
- warning communication — to prepare monitoring information into actionable messages understood by those that need them.
- In addition to the four elements, there are a number of cross-cutting issues that are critical to the development and sustainability of effective EWS; these include:
- effective governance and institutional arrangements;
- a multihazard approach to early warning;

- involvement of local communities;
- consideration of gender perspective, vulnerable populations and cultural diversity.

The most common view of EWS comprises a 'warning chain', a linear set of connections from observations through warning generation and transmitter to users. In the meteorological community, the term 'end-to-end' warning system is often used (Basher, 2005). The end-to-end concept aims to make forecasts and warnings more relevant and useable to end users. Such linear models are top-down and expert driven. They neglect the likely impact of the hazard and how warnings are communicated and responded to.

4.3.3 Effective early warning systems and warning communication

An effective EWS needs an effective communication system. Early warning communication systems are made up of the following two main components:

- The communication infrastructure hardware that must be reliable and robust, especially during natural disasters; many communication tools are currently available for warning dissemination such as cellular phone text messaging, email, radio, TV and web services. It is essential to assure the redundancy of communication systems, while emergency power supplies and back-up systems are critical in order to avoid the collapse of communication systems after disasters occur (Grasso, 2012). In addition, in order to ensure reliable and effective operations and to avoid network congestion, frequencies and channels must be reserved and dedicated to disaster relief operations.

- The warning messages: a critical element to influence the perception of risk and public behaviour is how the warning information is structured and what it contains. Generally, warning message content represents a source's assessment of the existence and seriousness of a threat as well as what the public should do to protect themselves (Lindell and Perry, 2004). A message delivered during a critical situation should contain:
  - hazard — short description of the physical characteristics of the hazard (nature and magnitude);
  - location — if possible, a certain position of the area affected by the hazard;
  - time (slow onset — occurring time, time estimated to reach the area; rapid onset — occurring time, rapid development);
  - guidance — the appropriate course of action necessary to prevent death or injury, providing protective action recommendations, including options for those unable to comply with recommended measures (e.g. evacuation orders);
  - pertinent details that should be included in messages; i.e. where to find shelter and the location of recovery supplies or aid stations that may not be obvious to the recipients of the warning.

Communication and dissemination systems should be tailored to the needs of individual communities (e.g. radio or television for those with access and sirens, remote disposals, warning flags or messenger runners for remote communities). Messages should incorporate the understanding of the values, concerns and interests of those who will need to take action.

Recent studies (Sellnow et al., 2015) have underlined the importance of using instructional messages (messages that take into account how people learn and the learning styles) during the response phase. The messages must include elements that not only explain the information, but also give its relevance (proximity, timeliness and personal impact) and motivate receivers to realise the value/utility of the message content and action (specific behavioural directions) that specify exactly what receivers are to do for self-protection.

A frequent problem is the weak link between the technical capacity to issue the warning and the local communities' capacity to respond effectively to the formal systems of warning (Basher, 2005). As such, it is important to recognise that these activities cannot be undertaken or directed by a single organisation, but require the coordinated participation of many different types of organisations that are committed at community level. National platforms for disaster reduction, stakeholder roundtables or interdepartmental committees should be empowered or established to organise the required coordination. The core technical agencies can play a key role by demanding the establishment of such mechanisms and supporting them with specialised technical information.

4.3.4 People-centred approach to early warning

To respond to these needs, the EWS has grown from a 'techno-centric only' paradigm to a 'people-centric' one where the 'end-to-end' and 'multihazard' components and their procedural norms start to bind together (Adger, 2000; UN, 2015). This new global move is led by the World Meteorological Organisation (WMO) which adopts a service delivery approach that should be making early warning information available and ensure the information is timely, reliable, dependable, usable, expandable, sustainable, responsive, authentic and credible (Ahmed, 2015). The WMO argues (WMO, 2014) for service-oriented actions that start from:

- user engagement and developing partnerships;
- evaluation of user needs and decisions;
- linking service development and delivery to user needs;
- evaluation and monitoring of services, performance and outcomes;
- sustained improved service delivery;
- development of skills needed to sustain service delivery;
- sharing of best practices and knowledge with others.

People-centred early warnings need to be clearly understood by people, easily and readily accessible to people; and timely: tied to response actions to be taken by people before, during and after the event.

The people-centred approach to early warning is promoted by the Hyogo Framework for Action, and focuses on how communities must understand threats in order to deal with them. Communities must be active receivers of information and be engaged in monitoring and such to facilitate the adoption of protective actions (Grasso, 2012). The 'people-centred' characteristic requires many systematic approaches and diverse activities spanning the four elements of EWS described above, such as (Basher, 2005):

- identifying target populations (especially the vulnerable and disadvantaged);
- interacting with target populations to determine needs;
- involving communities in exploring and mapping their risks and planning their responses;
- fostering the development by communities of monitoring and warning systems for local risks;
- generating public information tailored to target groups and making innovative use of the media and education systems;
- establishing people-focused benchmarks and performance standards for technical warning services;
- developing formal mechanisms for public representatives to monitor and oversee warning system design;
- using surveys to measure public awareness and satisfaction;
- creating monuments, publications, annual events and other anchors of public memory and learning;
- providing training on social factors for technical experts, authorities and communicators who operate the warning system;
- conducting research on factors that enhance or impede human understanding of and response to warnings;
- providing exercises and simulations to enable people to experience and practice warning interpretation and responses.

4.3.5 Effective early warning systems: lessons learned at community practice level

The International Federation of Red Cross and Red Crescent Societies (2012) has published an overview of successful practices from the field for the disaster risk reduction/management practitioners interested in EWS.

To be effective, warnings must have not only a sound scientific and technical basis, but also a strong focus on the people exposed to risk. Developing working relationships with partners, such as emergency managers and the media, and involving stakeholders in the development and review of the warning system is essential.

It presents guiding principles that could build a strong foundation for the design or strengthen EWS at any level. We present here the guiding principles per EWS component and for the cross-cutting themes.

The guiding principles per EWS component

- **Risk knowledge:**
  - K-1: Although risk knowledge exercises may not lead to early warning, all early warning must be founded on risk knowledge;
  - K-2: Accept that a community's priorities may not be your own.
- **Monitoring**:
  - M-1: Passive receivers of information do not save lives;
  - M-2: Some communities will need to drive their EWS;
  - M-3: Public displays of monitoring can motivate communities;
  - M-4: When hazards evolve, so must their monitoring.
- **Response capability**:
  - R-1: In EWS, we respond to warnings, not to disasters;
  - R-2: Strive to organise robust no-regrets response actions;
  - R-3: Embed response options by annually updating contingency plans with links to funding;
  - R-4: Practice makes perfect: test drive your response actions.
- **Warning communication**:
  - C-1: Clearly delegate responsibility to alert or mediate;
  - C-2: Do not fall into the sophistication trap for warning devices;
  - C-3: Use staged warnings (levels and colours) in dissemination.

Cross cutting themes – guiding principles

- CCT-1: Integrate within DRR — EWS is not a stand-alone;
- CCT-2: Aim for synergy across levels: community, national and regional/global;
- CCT-3: Insist on multihazard EWS;
- CCT-4: Systematically include vulnerability;
- CCT-5: Design EWS components with multiple functions;
- CCT-6: Accommodate multiple timescales;
- CCT-7: Embrace multiple knowledge systems;
- CCT-8: Account for evolving risk and rising uncertainty;
- CCT-9: EWS without borders: target the full vulnerability and hazard-scape;
- CCT-10: Demand appropriate technology;
- CCT-11: Require redundancy in indicators and communication channels;
- CCT-12: Target and reach disadvantaged and vulnerable groups;
- CCT-13: Build partnership and individual engagement.

In the changing landscape of EWS, stakeholders should continue to practice a combination of the approaches to build people-centric, multihazard, end-to-end and service-oriented EWS. The key for success would rely on:

- continued proactive governance;
- mobilisation of resources and capacity development for delivering the services (from all four streams) to the countries;
- making provisions for integrating EWS into the overall disaster risk reduction measures, which would be essential for keeping future harm away and moving ahead to build resilience at the centre of all activities (Ahmed, 2015).

4.3.6 Social media and communities in disaster: connecting the 'last mile'

ICT in general and social media in particular are an integral part of many people's lives today, including during times of crisis. As the examples illustrate in the previous chapter, crisis management authorities in many countries are using the new technologies to increase public awareness and preparedness for disasters, to alert and warn the public and to optimise situational awareness when crises strike.

While traditional radio and TV news remain important venues for sending emergency messages and updates to the general public (Collins and Kapucu, 2008), the widely accessible internet and wireless technologies allow for more flexible methods of communication (Cutter et al., 2007; Kapucu, 2006a; National Research Council, 2007).

For example, a great tool for both emergency managers and the public is Google Crisis Response, which organises emergency alerts and news updates relating to a crisis and publishes the information on dedicated landing pages. It also provides opportunities for donation in collaboration with international agencies such as Unicef, International Medical Corp and local relief organisations. Google also builds and provides tools to help crisis responders and affected people communicate and stay informed, such as Google Person Finder, Google Maps, Google Fusion Tables and Google Crisis Maps. Mobile apps have been developed with different demands and create a new approach for risk communication. The SMS alert system is useful in some cases for delivering alerts in an emergency, and GPS-related mobile apps (location sensoring and hazard maps) help to locate people in potential danger; some applications are developed as pre-disaster warning devices (educational apps). One example for such alert apps is the Katwarn system in Germany, which is currently used by disaster management agencies in more than 60 counties to inform the population about all types of disasters; it is available for Android, iOS and Windows phone platforms. Other examples for disaster alert apps are NINA, a general purpose disaster alert app. also from Germany, and SAIP, an app. provided by the French Ministry of the Interior to provide the population with alerts on major crises (with a special focus on terrorism alerts) (Klafft and Reinhard, 2016).

Social media use a decentralised, collaborative and network-based communication approach that allows citizens to generate data and share information about a hazard event irrespective of its geographic location and temporal extent, contributing to a resilient community.

Across various studies of emergencies and disaster events, numerous positive and negative aspects of social media have been identified (Reuter and Spielhofer, 2016):

- Social media promote cross-platform accessibility and a constant flow of information. During the Haiti earthquake in 2010, Ushahidi (an open-source multimedia mapping platform) allowed near-real-time mapping of the impacted population, which helped volunteers with rescue and response operations. Just-in-time information could be provided on how to cope with developing situations. During Super Storm Sandy in 2012, FourSquare (a location-based social network site) provided location information about visitors, which helped emergency responders with evacuation. The Louisiana Bucket Brigade, a local environmental justice organisation active along the Gulf Coast of the United States, created the Oil Spill Crisis Map after the 2010 Deepwater Horizon oil spill to provide information about community experience and risk perception to help with emergency management (Kar, 2016).
- Moreover, social media provide a framework for the work of journalists and for public discussion and debate. The United Nations Office for Outer Space Affairs established the Space-based Information for Disaster management and Emergency Response (UN-Spider) in 2006 to help with disaster risk reduction through stakeholder participation (UN, 2006).

Negative aspects of social media include the sometimes 'chaotic' or disorganised work of volunteers and the need for quality assessment, as well as the possible increase of task complexity and uncertainty for emergency services (Reuter and Spielhofer, 2016).

Social media can be understood as communication services that employ interactive online ICT (often referred to as Web 2.0 technologies) to enable the exchange of user-generated content. The term 'social media' embraces blogs, micro-blogs, social bookmarking, social networking, forums, collaborative creation of documents (via wikis) and the sharing of audio, photographic and video files (Balana, 2012). Social media are highly interactive 'digital tools that feature content users may generate, manipulate, or influence' (Giroux et al., 2013). In other words, social media encourage interaction and dialogue between users, creating an information space that is decentralised and devoid of hierarchy.

By providing community members with tools to engage in crisis preparedness, response and recovery, social media may have a role to play in building community resilience — a measure of a community's ability to respond to, withstand and recover from adverse situations (Dufty, 2012).

Most studies regarding social media use for emergencies focus on understanding how emergency response organisations adopt tools like social media and bring attention to members of the public as contributors and receivers in the emergency information arena. The 'crisis informatics' is the study of the social and technical (socio-technical) behaviours in emergency response, with a focus on the flows of information between the people and organisations involved. The approach attempts to account descriptively and theoretically for social behaviour that is made possible through technology (Hughes et al., 2009):

- Citizen reporting: the ability for people to report from on the ground during and after an event is analogue to ideas of citizens as 'sensors' — members of the public who detect, measure and report local emergency information — and as 'journalists' — members of the public who collect, report, analyse and disseminate news and information.

- Community-oriented computing: social media have been described as facilitating online communities where members share and seek information during times of crisis (Wang, 2010).

- Collective intelligence and distributed problem solving: social media have been shown to facilitate collective intelligence — where large, distributed groups of people solve complex problems (Vivacqua and Borges, 2010). Citizens may also provide geographically tagged localised and distributed reports — known as volunteered geographic information — of crisis events through social media. This geographic information can then be collated and mapped by volunteers who call themselves 'crisis mappers', using open-source mapping software such as Google Maps, OpenStreetMap or Ushahidi (Heipke, 2010).

- Contributions to situational awareness: an important contribution that social media offer in times of crisis is their potential to enhance situational awareness (Ireson, 2009).

The behaviours described above show ways to use social media in order to build community disaster resilience. These include (Dufty, 2012):

- developing social capital (e.g. networks, leadership and support systems) for disaster resilience-learning communities;
- informing others of the disaster risks in their community and discussing and planning what is being done to manage the risks and what they can do;
- engaging with others to help them prepare for a disaster;
- providing intelligence through 'crowdsourcing' to others (including emergency managers) before, during and after a disaster;
- communicating warnings and other information to communities during a disaster;
- providing support to people during and after a disaster;
- coordinating community response and recovery.

4.3.7 High tech/low tech communication and ethical challenges of social media

The London power outage of 2003 highlighted the importance of not relying on one single type of medium for warning and for informing the public (UK Cabinet Office, 2005) and reveals the vulnerability of social media networks to power outages, which in turn can leave healthy, affluent individuals in their mid twenties feeling very vulnerable. The guidance provided by the United Kingdom Civil Contingencies Secretariat to accompany the Civil Contingencies Act advises emergency responders to promote the use of resilient communication systems such as battery-operated or wind-up radios during emergencies as well as embracing social media platforms such as Twitter and Facebook to communicate during a crisis.

A woman in her late eighties, living alone in a small apartment with a meagre income from a state pension might appear vulnerable, but during the large-scale power outage in the

UK capital in 2003 she was able to heat a can of baked beans on a gas cooker and make a meal with some pasta, as well as share her experience with thousands of people through interactive media by using a landline telephone to call a BBC London local radio phone-in programme which was discussing the power outage.

Although social media will not replace traditional media in the foreseeable future, today many young people already heavily rely on social media to gain information, making this population hard to reach through established communication channels such as radio or television. Therefore, it is about striking a balance; social media tools are one of many communication tools to use.

By contrast, many well-paid workers in their mid twenties, who were employed in the main financial square mile of the City of London, might have been considered to be less vulnerable than the old woman, but the power outage exposed their lack of resilience — they could not use credit or debit cards to pay for food or drink due to the outage, they could not get any cash from ATMs and those that had cash could not buy provisions from supermarkets which were forced to close as their tills did not work. There were also additional security as well as health and safety concerns caused by the power outage (Civil Contingencies Act DVD, 2005). Wi-Fi networks were not available, denying internet access to the workers who commonly used email to organise their social life.

Those workers in their mid twenties who had a supply of ready-oven meals at home could not cook them as their microwave and electric ovens were not working and they could not travel further afield to areas with power because the London underground train system had stopped running and taxis, which were in great demand, would only accept cash payments (Civil Contingencies Act DVD 2005). With mobile phones lasting just a few hours before their batteries died or the back-up batteries at mobile phone masts lasting little more than 2 hours, the City workers in their mid twenties were revealed to be highly vulnerable and displayed little resilience as the power outage affected their service- and technology-reliant lifestyle (Civil Contingencies Act DVD, 2005).

A study by the University of East London, carried out in 2010-2013, used gaming theory to predict social media use during a mass evacuation event in London and one of the main conclusions was that radio, especially BBC radio, was still regarded as one of the most trusted and reliable sources of information during an emergency (Preston, 2013).

Emergency managers normally have to walk a very thin line between actions that may be deemed excessive and any failure to respond adequately that could be considered as negligence (Alexander, 2014). Also, considering the vulnerable people, any system of disaster response or risk reduction that depends on social media for access to its services risks excluding those people who lack access to the technology. 'Computer illiteracy' is a form of disadvantage in a world that has become dependent on digital communication for many services. It is only partially compensated for by the fact that, by relaying information by word of mouth, other people will be able to help a disadvantaged individual cope.

Other ethical risks are associated with a largely unregulated internet-based system of public mass communication. The use of social media for malignant purposes could potentially include:

- attempts to persecute people or damage their reputations (Boggs and Edwards, 2010);
- attempts to spread malicious rumour;
- efforts to create violent protest;
- attempts to organise terrorist activities.

4.3.8 Conclusions and key messages

Partnership

In this changing landscape of ICT, EWS and advent of social media, the key for success in disaster risk management would rely on user engagement and developing partnerships for gradual evaluation and improvements. This process may comprise comprehensive provisioning of: (a) evaluation of user needs; (b) evaluation and monitoring of actions, performance and outcomes; and (c) sharing of best practices and knowledge with others.

Knowledge

The opportunities and challenges that ICT and social media bring to development of disaster risk management foster a process that builds principles for action for communities of practice, creating a 'space of meaning' with theories for action, social change and instruments for implementation. Because each operational context is unique, stakeholders who aim to implement a policy or strategy have to learn their way into this implementation, often with a considerable need for innovation.

Innovation

This chapter presents some interesting and viable ways that disaster responders and people could rely on ICT and digital media to support their communities in times of disaster. In some cases, individual and community needs result in authority actions, moving toward the establishment of tangible resources that even endure over time. In other cases, ICT use might be ad hoc and temporary, resulting in the establishment of practices that prove useful to the community and can be used as tools for continuous adaptation and innovation.

4.4 Good practices and innovation in risk communication

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4.4.1 Introduction

In this chapter we deal with the thorny issue of innovations and 'best practices' in risk communication. Individual examples of best practice developed from both research and by enlightened practitioners (c.f. Coleman, 2013) are not difficult to find. Seeger (2006) identified the following ten 'best practices' in risk communication:

1. Process approaches and policy development for and responding to crisis are critical to success.
2. Pre-event planning, creating teams, fact-finding protocols, messaging and delivery are vital.
3. Partnerships with the public.
4. Listen to others' concerns.
5. Exhibit honesty, candor and openness.
6. Collaborate and coordinate with credible sources.
7. Meet the needs of the media and remain accessible.
8. Communicate with compassion, concern and empathy.
9. Accept uncertainty and ambiguity.
10. Provide messages of self-efficacy by issuing specific information telling people what they can do to reduce harm; these messages can help restore some sense of control over an uncertain and threatening situation (Seeger, 2006).

This was developed further by (Heath, 2006) who suggested two further best practices:

1. Realise that crisis response is a narrative and that you are telling a story.
2. Be committed and able to deliver on the promise to be the first and best source of information.

In the early 2000s these issues were seen as best practice and, given the relative paucity of research in this area, are easily identified. The complexity, scale and scope of both man-made and natural disasters now demand new types of response and have led to a blossoming of research and development activity to address these societal challenges. Equally, both the role of new technologies and new communication patterns have enabled new forms of practice to emerge. The best practice discussed by Seeger (2006) and Heath (2006) remains relevant but has now been embedded into processes and protocols discussed elsewhere in this chapter. We refer, therefore, to 'innovation' and 'emerging practice/improving practice' rather than 'best practice'.

Innovation can be described as the process of moving knowledge gained in research to the development of a physical product or changing the way things are done which can improve the quality of life. However, innovation and risk do not necessarily make good allies. Innovation by its nature suggests levels of uncertainty and risk (HM Government Office of Science, 2014); it is therefore unsurprising that different authors (Kasperson, 2014; Renn, 2014; Árvai, 2014; Pigdeon, 2014) have agreed that risk communication practices and processes have changed little over the last few years

(Kasperson, 2014). Furthermore, Pidgeon (2014) points out that increasingly complex, more frequent and costly disruptive events require scrutiny of both emerging technologies and changing risk identities in society to develop the strategic capacity to address these fundamental risk communication problems 'in appropriate methods for situating 'values' in public and stakeholder engagement and in fostering citizen deliberation for the wider public good'. However, by surveying the evidence from current research about what works, the relationship between public sector organisations and private citizens in fostering innovation in risk communication can be tested and its effectiveness determined (HM Government Office of Science, 2014).

Innovation has been categorised in a variety of different ways from process innovation, product or service innovation, governance innovation or conceptual innovation (De Vries et al., 2015). We focus on the following three aspects of innovation and improving practice in risk communication by identifying particular issues and areas of innovation which are challenging either for practice or areas of intense activity.

Firstly we deal with innovation and practice in the process of risk communication, focusing on one of the more significant areas of the former: new emergent approaches that reorientate practice around communities and new and evolving decentralised approaches. Secondly, we look at new communication patterns, emphasising the challenges of communicating with millennials and of cross-border communication. The third chapter of this chapter pays particular attention to technology infrastructure concerning innovations which allow rich media channels to be utilised. The final chapter discusses the challenges faced in embedding these innovations into practice.

4.4.2 Risk communication and citizen participation

Research indicates that messages need to be culturally adapted to different country settings. Investigated by the current EU BeSeCu project as well as by the EU E-COM@EU project, findings indicate that cultural differences extend from mere age differences to a national context with regard to the most popular social media tools and national norms for communication style and tone.

Governments (national, regional and local), emergency management (responder) organisations and other public service bodies are traditionally risk averse and mostly rely on communication methods that reflect a view that aims to align lay perceptions with expert views of severity (Árvai, 2014) rather than participatory models that recognise local citizen expertise and knowledge. Further, Höppneret al. (2012) suggest that within the current pan-European communication practices, knowledge on the (target-specific) suitability of different communication forms is rarely translated into the field. There has been, however, a recent paradigmatic shift in disaster risk management moving from a top-down focus to what has been termed a 'people-centred approach'. While this approach is still emergent and contested (Scolobiget et al., 2015), it has led to a range of innovative practices and approaches, such as the alignment of people-centred decentralised approaches. The development of digital technologies and social media platforms (e.g. the use of social media in the Haiti earthquake, the Queensland floods in Australia and Hurricane Sandy in the United States) has led to new ways of delivering better targeted, actionable risk information to diverse publics across multicultural, multiagency and multi-jurisdictional boundaries.

Communication needs to be culturally and context specific while it engages citizens "as sensors" and contributors in the unfolding "story".

Due to its popularity and collaborative, participatory, decentralised and accessible nature, social media allows information to pass quickly to multiple publics and organisations; thus extending the reach of emergency responder organisations, enhancing risk communication, improving situational awareness and furthermore providing traceable geographical and temporal data for monitoring disaster events in real time (OECD, 2012). Related research also indicates, however, that despite the shift from mass media to social media as a complementary platform and the several different identified uses and functions (preparedness, warning and informing, pre-event signal detection, connecting communities, developing resilience and aiding recovery), social media is still emergent (Houston et al., 2015).

To address these issues there has been considerable investment by the EU through its seventh framework programme for research and technological development (FP7) and Horizon 2020 frameworks in risk communication research. An innovative, groundbreaking project — PetaJakarta.org — combines different sources of data and citizen participation to produce real-time intelligence-led information to create a shared situational awareness and to promote resilience (Holderness and Turpin, 2016).

PetaJakarta is an example of applying new concepts such as geosocial intelligence frameworks, and demonstrates an evolutionary process from passive spatial and temporal data mining techniques to 'big crowdsourcing'. Geosocial intelligence frameworks rely on a deep understanding of the information ecosystem within which social media platforms operate. The challenge in gathering 'intelligence' is to extract knowledge from the 'noise' generated by such platforms so that users, governments and other actors can make 'actionable decisions in a time-critical manner' (Holderness and Turpin, 2015). Four principles underlie such frameworks:

1. Reliable, free and open-source software that enables the gathering, sorting and displaying of useful disaster-related information.
2. 'Big crowdsourcing,' wherein users on a social media platform are actively encouraged to share information relevant to a given situation or anticipated scenario.
3. A participatory approach and co-management that values the peer-to-peer sharing of situational information within the same platform that is used by government agencies and first responders who can transparently monitor and cross-check the data being shared.
4. Open data, so that all users can inspect the software, review the system and develop complementary tools and technologies that further enhance resilience within the information ecosystem.

This 'people as sensors' paradigm (which echoes the work of Scolobig et al. 2015) was used by PetaJakarta to contact many more Twitter users than any human could hope to do and allowed the network of users to grow organically through linking to personal networks. The map used by both citizens and government agencies created a reciprocal communication interface between citizens, the PetaJakarta project and the government. By engaging with government civil defence agencies and noting their operating procedures, including interaction between Twitter accounts @petakjt and @BPBDJakarta to disseminate (retweet) key information, the project was seen as credible and legitimate by other government departments and the public. Major challenges for this project were:

- how to ensure the verification of very big crowdsourced data; and
- how to engage citizens to participate actively in sharing their data.

Verifying the data acquired from Twitter was of critical importance to the project. User-generated reports were cross-checked in a number of different ways: by cross-referencing data with tweets from the same location; Twitter feeds from government agencies; electronic media such as television reports and internet news sites; and by recognising active users who frequently tweet reliable information.

To engage as many citizen users as possible, a community inclusion strategy was designed to use concise, action-oriented messages such as 'See a flood. Tell Us' and also to adopt a user-centric approach by encouraging users to retweet any messages received from the project to their own personal networks. The big crowdsourcing element of the project was also emphasised by highlighted messages promoting the benefits of greater use of PetaJakarta such as 'The more people use PetaJakarta, the better the map will be' (Holderness and Turpin, 2015). The strategy sought to highlight the community resource element of the project by adopting a non-moralising, opt-in approach to include citizens as partners in the sharing of real-time information and situational awareness regarding flooding rather than just being the recipients of emergency or information messages.

The example of the PetaJakarta project demonstrates how innovative participatory, collaborative approaches can be extended to gather real-time information through the use of social media platforms and open-source software. Furthermore, the utility of the concept of a Geosocial intelligence framework appears to be transferable given the global nature of the social media platform and the availability of the open-source software, making the concept adaptable to the European context.

4.4.3 New communication patterns

This chapter looks into the use of social media and mobile technologies in the communication process with younger (millennial) demographics. Messages, urgency and level of planning change with the stage in the disaster cycle and planned versus reactive settings are highlighted. The place of such media in a wider set of media used in a range of disaster settings is examined and discussed, as are the opportunities to extend messages from traditional media to include, and take advantage of, newer forms of communication.

Eurostat statistics suggest that younger people are more likely, in Europe as elsewhere, to have access to more up-to-date smartphones as well as to information via tablets and gaming consoles. Furthermore, younger people are less likely to engage with traditional channels such as radio and broadcast media/print press and more likely to make use of social media such as Twitter, regarding this as a legitimate source of information, more than older citizens would (Bruns and Burgess, 2014).

Conflicting previous research (such as Austin et al. 2012) has implied that traditional media was preferred — at least a few years earlier —as a credible source of information, and similarly (according to Vihalemm et al. 2012), the trust in traditional media outlets has been seen to rest upon the belief that communication institutions have the proficiency to assess and estimate information to obtain an adequate overview of a situation and to calculate risks and make decisions when broadcasting.

Even though decreasingly, information is still sought through traditional mass media sources (namely from broadcasting companies), to some extent regarded as more credible sources of information. According to the findings of a survey of 1 034 citizens across 30 European countries, only 13 % of respondents perceived information on social media to be more accurate than that of traditional media channels. In fact, nearly half (44 %) of the respondents did not agree with this statement (Reuter and Spielhofer, 2016).

To this extent, there have been implications that — through its social, interactive, local, rapid, unfiltered and timely qualities as well as convenience and personal nature — social media serves as a medium leading towards providing relevant information (Posetti, 2012; Austin et al., 2012). This is also supported by the previously mentioned survey, showing that citizens perceive information provided on social media during emergencies as more accessible than information provided via more traditional media channels such as TV, radio or media websites (Reuter and Spielhofer, 2016). The change could be explained through media convergence; the interlocking of different types of media (text, audio and video) and content (news, popular culture, etc.) on online forums (and further on social media sharing) has improved and simplified access to any kind of information via smart devices that was previously sectored behind different media (television, radio and print press). Key social apps such as Facebook and WhatsApp also have a useful characteristic in that it is easy to share information, and the functionality of the apps make it clear which information is more recent or has updated other information; therefore, these apps facilitate the creation of shared situation (or information) awareness.

It is important to handle the transition from traditional media to social media, while fostering trust and reducing rumours and misinformation.

A key issue is that of engaging communities and citizens rather than purely disseminating messages. This was investigated comprehensively by the Public Empowerment Policies for Crisis Management (PEP), which suggested the integration of younger citizens in responsibilities for such communication to improve relevance and access to that demographic. A related effect is the low reliance of EU communities on self-help (POP ALERT project), with 'the authorities' being expected to lead efforts as well as be a source of information. POP-ALERT suggests that community resilience can (and should) be strengthened, and highlights social media and messaging as key tools in engaging younger demographics as well as in providing resources such as toolkits to support such development. This is further supported by Duffy (2012), who identifies the use of social media in such efforts to improve resilience and preparedness.

Once a disaster has occurred, the emphasis shifts from preparedness messages to messages designed to update and inform. There has been significant EU action to develop appropriate infrastructure, which allows connectivity and access to information during the course of a disaster that may have compromised such communication systems (IDIRA and PPDRTC, for example). For many people in such a situation, the priority becomes the ability to 'track' the disasters and gauge the likelihood of being affected. For example, residents in a flood area not yet affected by floodwater need to know whether they are in an area where they should stay put, prepare for the eventuality of evacuation or evacuate.

Another interesting notion is how the source and form of crisis information affects the public's information-seeking behaviour. Based on their study on such behaviour during crisis situations, Austin et al. (2012) suggest that people are more likely to use the same type of media to seek information as that from which they initially heard about the crisis. Their findings extend to the channel complementarity theory, which proposes that users of a medium that serves a particular functional need are also more likely to choose other media relevant to serving that particular function or need (Dutta-Bergman, 2006).

Similarly, previous research has established that the effectiveness of crisis communication is positively influenced when the social position of the communicator or the channel is 'close' to the recipients' everyday lives (Trumbo and McComas, 2008; Lachlan et al., 2007). Furthermore, the public's implicit or inherent presumptions regarding the source or channel of information may affect further information behaviour (e.g. seeking more information about threats or ignoring it) (Vihalemm et al., 2012). Bird et al. (2012), for example, highlight the use of Facebook groups — both official and community generated — in the Queensland floods in Australia. In this setting, the ability to trust the messages received is key and information is likely to be sought, particularly by younger people, from multiple channels in order to 'cross-reference' advice and information (EU public empowerment policies project). The issue of trustworthiness of messages also needs to be highlighted. Credible sources are needed to convey messages and should take advantage of the 'spotlight' period of public attention at the height of a disaster to ensure effective messages are disseminated. This issue of trust is specifically addressed by the E-COM@ EU project.

Post-incident preparedness messages can be continued and will have, for a period of time, a higher level of attention, especially with regard to the specific type of incident that has occurred, although, depending on the nature of the disaster, communication systems may be affected over a very short or an extended period of time (e.g. in the case of infrastructure damage after a flood or earthquake).

Cool et al. (2015) highlight the role of social media with younger citizens in post-disaster risk communication after Typhoon Haiyan in the Philippines as well as the lack of an infrastructure of social media use during the disaster itself. Yasuda et al. (2016) highlight the role of in-school projects in preparing younger citizens in the same setting, as do Schiavo et al. (2016) in a broader health-promotion context.

Communication with younger demographics shares one key issue with wider issues of communication; the requirement for a capable and resilient infrastructure to support communication. This is being addressed both as a technical issue (e.g. provision of resilient broadband —PPDRTC project) and through effective middleware to improve collaboration among message providers (e.g. Disaster and IDIRA). In terms of preparedness, such communication capability is available to many people (and arguably especially to younger people) for most of the time through 4G wireless networks, broadcast media and targeted project interventions.

Cyber security is also raised as a risk factor by projects including the EU public empowerment policies project, as is the quality of information sources feeding into messages — especially at the reaction stage; EU Proactive project being an example of a technical approach to this issue. The need to take a multidisciplinary and multichannel approach to communication rather than targeting specific groups — such as younger people — solely via a 'preferred' channel is highlighted by the EMBRACE project. Furthermore, studies related to crisis communication in real-life situations (e.g. Greater London area riots in 2011 and the swine flu epidemic in 2010) have highlighted the role of proactive and interactive methods of communication as well as timely reaction in both enabling trust and increasing communicational reach.

These studies emphasise the importance of interaction and participation in online communication rather than merely relying on one-way information dissemination. Prompt reaction and interaction can prove to be pivotal in avoiding a communicational void (especially from the public authorities) — and in preventing such a void from being filled by other actors — as well as in establishing dialogue and trust towards citizens, but also in increasing communicational reach through shares, likes and recommendations (Denef et al., 2013; Tirkkonen and Luoma-Aho 2011). A further risk issue in the use of social media — therefore disproportionately affecting younger citizens — is the potential (Alexander, 2014) for inaccurate information. Rumours, either naïve or malicious, can be rapidly and widely disseminated in advance of accurate information, and can potentially reduce its impact or fully eclipse it when it does come. For example, according to a study by Gupta et al. (2013), rumours and fake content covered 29 % of the most viral content on Twitter, while 51 % of the content was generic opinions and comments and only 20 % relayed true, factual information.

A recent study also found echo effects (i.e. the dissemination of older tweets with fake information) but also self-correcting mechanisms of social media communities when verifying and dispelling online rumours during crises (Jong and Dückers, 2016). There are also imbalances in national contexts; Mudhavanu et al. (2015), for example, highlighted the lack of involvement of younger citizens in disaster risk communication in Zimbabwe.

4.4.4 Technology Infrastructure

A key area for technological innovation in DRM relates to the social and technical challenges concerning personalisation while achieving a shared situational awareness among the emergency services and citizens. Shared situation awareness refers to information that is shared, including updates of the information among a group of people, for example as achieved by projects discussed above. Shared situational awareness is often defined for team performance (e.g. Cuevas et al., 2011), yet is also relevant in crisis management (e.g. Van De Ven et al., 2008; Wolbers and Boersma, 2013). Personalisation is directly related to cultural and contextual diversity in Europe, including multilingualism, the EU-wide mobility of its citizens and serving citizens experiencing a disability or requiring special needs (e.g. deafness, speech impairment, etc.). A number of EU FP7 and Horizon 2020 projects are currently addressing these aspects to enable rich(er) communication between emergency services and citizens, including bidirectional voice, real-time text, video and data: 'total conversation' with rich data (personal, medical and location data). A non-exhaustive overview can be found in the appendix.

Current communication means that rely mainly on voice calls via landlines or mobile phones as services for exceptional cases are only partially supported by SMS, email, fax and text relay. The advent of social apps and the wide availability of smart devices enable the implementation of a total conversation model that combines audio, real-time text, video and data-sharing to serve all citizens, including those experiencing a disability and requiring special needs. However, typical challenges encountered are related to standardisation and customisation: standardisation is necessary to ensure European-wide accessibility to emergency services, while customisation is necessary to allow the implementation of specific apps, products and services for specific audiences.

Another open challenge is multilingualism and multicultural personalisation (Stephens and Malone, 2009). Each European country (and beyond) hosts many citizens who do not speak the native language, including tourists, expats and immigrants, but also citizens who use sign language (i.e. due to speech or hearing impairments). During crises, effective and efficient communication is of utmost importance, and having control over the quality of translations of communications is also an applicable challenge to emergency services (Manso et al., 2016). The operators and first responders engaging in dialogue with citizens may need automated support in communicating effectively with citizens with different language proficiencies and cultural backgrounds (Manso et al., 2016). Projects such as NEXES, Insign and SignSpeak address the challenge of fostering communication with (national and international) sign language users.

Technical standardisation may be hampered or fostered by the current developments of regional and national 'emergency apps'. Examples of national apps with integration into the emergency services' systems and work processes include the BurgerNet app. (n.d.), the WhereAREU app. (n.d.), Greater Manchester Police app. (n.d.), and others. A possible disadvantage is a plethora of special-purpose apps that only function within a specific region. Other apps, such as the BurgerNet app., have functionality for cross-border cooperation and pave the way for standardisation efforts. An innovation investigated by the NEXES project is to provide standardisation to the 'back-end' of these apps through providing reusable libraries. This ensures flexibility by app. developers to build any desired app. with a harmonised integration with emergency services. An advantage of such an innovation is that, potentially, such apps can function everywhere in Europe and beyond.

Enable communication between many parties through different (non-) digital media, securing proof of origin, tamper proof contents and discovery of updated information.

A social and technical challenge for emergency services is to engage in 'crowdsourcing': mobilising citizens to provide information on specific topics and/or engage in certain actions. However, both the advantages and disadvantages of crowdsourcing concern privacy, handling information from participants with malicious intent, detecting false positives, etc. Furthermore, participant motivation and engagement are of importance, especially when frequent updates of information from crowdsourcing are required (Liu, 2014).

Although general media coverage cannot, and likely should not, be restricted, communication with and by emergency services may need to become more focussed and targeted. A challenge for risk communication is to target specific risk communication to a specific audience, possibly deliberately excluding specific citizens, e.g. unaffected citizens (Manso et al., 2016).

Another challenge concerns the party that takes the initiative. Typically, citizens take the initiative by calling emergency services in an emergency. Emergency services, however, take the initiative prior to an incident/situation in providing information to (groups of) citizens. An innovation to be investigated in social and technical implications concerns how emergency services can contact a citizen, which could be a response of 'calling back' or when losing connectivity (Manso et al., 2016). Alternatively, there is the case of proactive communication: initiating communication before a hazardous situation unfolds. Unexpected communication by emergency services and other authorities towards citizens may raise issues regarding privacy.

Crisis informatics (Palen et al., 2007) is a documented phenomenon that illustrates how people in and out of the disaster go online through computers using Web 2.0 applications, cell phones and other personal devices to provide, seek and broker information in times of emergency.

For example, results found in Soteria indicate that citizens consider authorities' presence in social media as valuable and reassuring during emergency situations (Jäntti et al. 2016). This directly implies that trust is an important facet of risk communication (Coombs and Holladay 2014). Apart from social and political aspects of trust, a number of security considerations are of importance regarding the message(s) sent by certain (trustworthy) parties (Fruth and Nett, 2014; Tanenbaum and Van Steen, 2007):

- Non-repudiation: no message can be changed or tampered with; it is the original message with original author, source location and timestamp.
- Signed: any message can be traced to its author (the originating party).
- Relationships: any message explicitly refers to another message, including an annotation of the type of relationship, such as 'is an update of'.
- Distribution: any message can be shared and distributed, without changing the above properties.
- A challenge is to explore these technical considerations further so that messages sent by (authorised) parties can be received, inspected and shared by any recipient. Of importance is the ability to check for 'updates' and to have the built-in technical means to assure that citizens can be notified of updates in a timely fashion. Information-bound security approaches (Xylomenos et

al., 2014) may be of relevance.

A typical technological challenge during a crisis concerns the availability and reliability of communication networks. Numerous national and EU-funded projects (too many to list here) investigate new technologies and solutions for telecommunication infrastructures and network robustness. Nevertheless, it is prudent to assume that communication networks may be (temporarily) disabled, congested or unavailable during a crisis. Given this assumption, a challenge is to ensure that (a) information can be communicated to citizens and that (b) information can be inspected for authenticity and timeliness. The security considerations with regard to messages, formulated from the trust perspective, also apply to non-technical communication. Is it possible to deliver messages without using

BOX 4.1

Project overview (non-exhaustive)

- BeSeCu (Behavior, Security and Culture) project. Understanding culture in crisis behaviour.
- COMPOSITE project.Comparative police studies in the EU (www.composite-project.eu).
- DISASTER. Data Interoperability Solution At Stakeholders Emergency Reaction Novel methods to enhance cross-border emergency response (www.disaster-fp7.eu).
- E-COM@EU project. Effective communication in outbreak management (www.ecomeu.info).
- EMBRACE. Building Resilience Amongst Communities in Europe. (www.embrace-eu.org).
- HeERO 2 project. Harmonised eCALL European Pilot (www.heero-pilot.eu)
- IDIRA. Interoperability of Data and procedures In large-scale multinational disaster response actions. (http://www.idira.eu/).
- INSIGN. European Commission DG Justice and Consumers pilot project regarding improving communication between deaf and hard of hearing persons and the EU (www.eu-insign.eu; not online anymore)
- New information system for the national emergency response centre of Finland (http://www.112.fi/en/the_erc_reform/new_information_system)
- NEXES. NEXt generation Emergency Systems (www.nexes.eu, Manso et al., 2016)
- Online and mobile communications for crisis response and search and rescue actions (isar.i112.eu) (Flizikowski et al., 2014; Manso and Manso, 2012)
- Online and mobile communications for emergencies (soteria.i112.eu) (Jäntti et al., 2016)
- PEP project. EU Public Empowerment Policies for Crisis Management (www.crisiscommunication.fi/pep).
- POP ALERT project. Solutions to better prepare European citizens and authorities during large-scale crises.
- PPDRTC project. Public Protection and Disaster Relief — Transformation Centre. Roadmap to emergency communication (www.ppdr-tc.eu).
- PROACTIVE project. Terrorism detectors. (www.proactiveproject.eu).
- Project Slándáil, which aims to build and test a prototype system for managing disaster emergencies by fusing information available in different modalities in social media with due regard to ethical and factual data provenance (www.slandail.eu)
- REACH112. Responding to All Citizens needing Help (www.reach112.eu)
- REACT. Reaction to Emergency Alerts using voice and clustering technologies (www.react-ist.net; not online anymore)
- Software to understand sign languages (www.signspeak.eu)
- Use of new communications and social media to support citizens during crisis (www.projectathena.eu) (Gibson et al., 2015)

digital communication infrastructure, while retaining these trust-enhancing aspects? The challenge here lies in allowing citizens to distribute messages using various media, including but not limited to paper, photographs, photocopy, etc.

4.4.5 Conclusions and key messages

In this subchapter we have identified a number of areas of practice, many of which reinforce existing tenets of effective practice: communication is reciprocal and risk communication is about increasing the quality, timeliness and accuracy of situational awareness. We also point out the influence of technological innovations and current innovation challenges that lie in realising total conversation and crowdsourcing capabilities, personalisation for citizens, integration with emergency services, enhancing trust in (official) communication and standardisation with and beyond the EU. Research has indicated that many of the challenges related to information sharing during major incidents transcend technology issues (Allen, Karanasios and Norman 2014). These new innovative processes can, however, be seen as a double-edged sword, bringing not only benefits but also new risks and challenges. As Liegl et al. (2016) state, it is also important to note the importance of the consideration of ethical, legal and social issues (ELSI) related to these new innovations.

Partnership

Governments (national, regional and local), emergency management (responder) organisations and other public service bodies in disaster risk management are slowly shifting from communication methods that reflect a view that aims to align lay perceptions with expert views of severity to participatory models that recognise local citizen expertise and knowledge. A key issue is that of engaging communities and citizens rather than purely disseminating messages, that is, moving from a top-down focus to what has been termed a 'people-centred approach'. The development of digital technologies and social media platforms (e.g. the use of social media in the Haiti earthquake, the Queensland floods in Australia and Hurricane Sandy in the United States) has led to new ways of delivering better targeted, actionable risk information to diverse publics across multicultural, multiagency and multi-jurisdictional boundaries.

Knowledge

In this context, it is wise to consider the 'dark' or unexplored areas of research and practice in risk communication. In a recent structured literature review of research focusing on innovation within the public sector, De Vries et al. (2015) noted that only 7 % of the literature reviewed dealt with technological process innovation and that interorganisational innovations have not been thoroughly investigated. It is perhaps interesting that much of the work discussed here deals precisely with these areas: interorganisational innovations and technologically enabled process innovation. However, it is also telling that whilst the studies we have identified discuss the nuances of the technologies and processes to 'improve practice' or demonstrate 'innovations', they singularly fail to discuss the mechanisms by which the innovations are stabilised or grown in terms of institutionalisation, scope and function.

Innovation

The key challenges for innovation in disaster and risk communication lie not in the generation of innovative practices but in the implementation of mechanisms by which innovations and improving practice are diffused and moved from a state of emergence to wide-scale adoption. Rather than generating innovative approaches, we would suggest that embedding and diffusing innovations is the key area that both policy and practice must address.

Recommendations

The approach to communicating disaster risk in recent years has been shifted from a top-down, 'one size fits all' approach to a more democratic, engaged and inclusive one. It implies partnership between policymakers, practitioners and citizens of all backgrounds. In a society in which people have the opportunity to inform themselves about a wide variety of risks through various media channels, one-way media campaigns that tell people how to prepare, respond and recover from a disaster are not effective. Instead, engaging in a dialogue with local communities to understand the historical and local context is an important fundament for future risk communication that focuses on stimulating resilient behaviour:

- words used for risk communication should be inclusive and emphatic in order to contribute to effective communication and support and eventually to more resilient coping strategies of those affected by a disaster;
- since the people's response to disasters is influenced by past experiences and local cultures, risk communication should be based on the understanding of local risk perceptions and capacities.

Likewise, the practices of disaster and risk management should rely on a comprehensive approach to decision-making. Participatory models emphasising engagement with and empowering of local communities through joint preparation, planning and information crowdsourcing have emerged, enabled by increasing digitalisation. Those involved in risk communication should:

- realise that collecting, sharing and disseminating disaster information is not neutral, as it has an impact on how people perceive risks and deal with the consequences;
- bottom-up, people-centred and participatory processes need to be established to ensure collaborative and inclusive decision-making;
- make sure that the collection, analysing and modelling of crisis data is done in a transparent and ethical way to avoid privacy infringements, unauthorised dissemination of personal information, inequality and irresponsible behaviour.

ICTs play a vital role in risk communication. New communication tools and innovations, including social media, Wireless Emergency Alerts (WEA) and the use of mobile and online communication tools, might help people to find more relevant information on disaster risks. At the same time, innovation in risk communication should never be a goal in itself:

- it is critically important to invest in the implementation of mechanisms by which innovations can improve communication practices, including interorganisational collaboration;
- the communicator and/or the channel's social position should be as close as possible to the recipients' everyday lives as this will positively affect the

outcome of risk communication;
- using personalisation of risk communication that is related to cultural and contextual diversity is a key ingredient of a successful communication strategy;
- since critical information infrastructures can be affected by disasters (e.g. resulting in large-scale power blackouts), governments should invest in reliable, redundant and sustainable infrastructures, but at the same time take measurements to go beyond the infrastructure by investing in risk knowledge, monitoring and risk capacity and early warning systems.

The above efforts together will support a more balanced, inclusive and systematic approach to risk communication and will eventually lead to a more resilient European society that has to deal with increasing risks.

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Introduction

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4.1 Public perception of risk

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Chapter 5

Managing disaster risk

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5 Managing disaster risk

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Introduction

The European region is exposed to a wide range of natural hazards such as storms, droughts, heat waves, floods, earthquakes, avalanches and landslides that continuously cause human and economic loss.

Despite the European wealth of expertise, knowledge and know-how in disaster risk management (DRM), statistics show that vulnerability to hazards in the region is increasing.

DRM comprises a systematic process of using administrative decisions and organisational and operational skills and capacities to implement policies and strategies, and coping capacities of society and communities to lessen the impacts of natural hazards and related environmental and technological disasters. This concept includes all forms of strategies, policies, plans and activities aimed at minimising disaster impacts on individuals and society.

This chapter examines the scientific contribution to understanding these processes and institutions across Europe. These are described in four subchapters, divided up in a similar way to how DRM functions and are often separated conceptually across a disaster management cycle. The disaster management cycle commonly includes four types of measures needed to manage disasters: mitigation and preparedness (before a disaster) and response and recovery (after a disaster).

These measures are broadly aligned with the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR), which adopts the idea of managing disaster risk as opposed to managing disasters, whereby action is needed to do the following.

- Reduce existing risk: a set of measures, known as 'corrective risk management', similar to the commonly used concept of 'mitigation'.
- Avoid new disaster risk: activities to address and avoid the development of new or increased disaster risk, known as 'prospective risk management', similar to what are often referred to as 'prevention' measures.
- Manage residual risk: activities that strengthen the resilience of individuals and societies to risk that cannot be effectively reduced, including preparedness, response and sometimes recovery activities (those that do not actually avoid new disaster risk by, for example, relocating populations in the aftermath of a disaster) as well as risk transfer and financing activities.

Prevention and mitigation; preparedness and response planning; post-disaster recovery (to new risk); and risk transfer and financing are the major topics of this chapter. The focus in Chapter 5.1 is on studies of disaster mitigation and prevention presenting a range of structural (e.g. building codes and their enforcement and structural protection measures) and non-structural (e.g. land-use planning and zoning) measures. Critically, all disaster prevention and mitigation measures need to be identified on the basis of risk assessments, and the use of these across Europe is reviewed in this chapter.

Mitigation and prevention measures in Europe are widely considered to be more cost-effective than post-disaster interventions. This is predominantly based on an analysis of the benefits arising from avoided loss. Economic analysis methods have been applied to gain a better understanding of the economic benefits of mitigation and prevention. Yet recognising and appraising the wider co-benefits of investing in mitigation and prevention could make an even more convincing case. This chapter examines some of these broader benefits to society and to the economy.

Human exposure to natural hazard risk is mainly caused by settlement and other economic developments in hazard-prone areas, but this risk can be managed through spatial planning and regulations; national spatial planning policies may involve cooperation with other countries. Within cross-boundary river basins, countries may jointly seek for policies to control flood waters through spatial planning measures. An example are the flood retention areas in the Rhine basin, which aim at storing flood waters upstream in Germany to lower the risk of flooding downstream in the Netherlands.

Disaster preparedness and response addressed in Chapter 5.2 is embedded in complex ethical, legal, social and political contexts, and broad values and principles are needed for emergency response that transcends boundaries.

This necessitates cooperation between regional, national and international communities. The EU Community Mechanism for Civil Protection is developing several tools to support this, including the European Emergency Response Coordination Centre (ERCC) in Brussels as well as a Common Emergency Communication and Information System (CECIS). A key issue for preparedness is how societies can translate these broader values and principles of emergency response into social, organisational and technical innovation.

The professionalism and coordination of preparedness for response by civil protection agencies has significantly advanced in recent years alongside a desire to give citizens increasing responsibility for their own preparedness. There has been a strengthening of the value of citizens themselves in preparedness and response planning, with social groups playing an important role during a disaster to help manage emergency response. Strengthening social cohesion and trust before a disaster can increase the response's effectiveness. Extensive flooding in 2007 in Kingston upon Hull in the United Kingdom, for example, stimulated a range of spontaneous actions by local residents, including assisting with evacuation, giving care and support to vulnerable neighbours, protecting houses against floodwater and giving medical assistance.

Chapter 5.3 presents post-disaster recovery as an opportunity for economic development and regeneration. The recovery process is multidimensional and progresses at different rates for different people, businesses, institutions and places affected by a disaster. Institutional fragmentation and short-term planning can hinder recovery processes and often result in new risks being created. Thus, cross-scale and longer-term risk management strategies are needed in recovery, integrating different stakeholder perspectives and knowledge and coordinating across policy domains.

For earthquake and other types of reconstruction there is not a 'one size fits all' model, but decisions need to be discussed in advance with the citizens, taking into account suggestions and explaining the limits of time, space and budget. Territories are different, available scientific and technologic support evolves and the population's expectations can change through time: a mature civil protection system looks for tailored solutions building on previous experience while exploring new alternatives.

Economic recovery occurs at various scales after a disaster and the economic system will unlikely return to a pre-disaster state, yet measures can be taken to support and accelerate the recovery process. Higher levels of assets give a wider range of options and opportunities following a disaster and can speed recovery, as can access to formal credit and grants. Families, neighbours and social networks can help people to recover their assets.

Accessing financial resources after a disaster is critical to rebuilding and maintaining essential functions. Nonetheless, the policies supporting economic recovery should not focus solely on financing. A mix of policy initiatives is needed to build resilience after a disaster: from the design of early warning systems (EWS) tailored to specific audiences to the development of efficient regulations. Overall, combinations of financial support with other market support and service provision are needed.

People's psychosocial recovery after disasters is a complex, multidimensional process that is also linked to the measures taken before disasters occur, to the social and economic circumstances of those affected, to the actions taken to rebuild and restore assets and to the services provided after disasters. Research demonstrates that people's recovery in the short and medium term can be promoted through a psychosocial approach, with interventions made universally available to reduce suffering and risks of people developing mental disorders.
Disasters can undermine development progress and financial and economic stability and well-being, and so a sound risk financing strategy is needed to lessen these impacts and speed up recovery and reconstruction (Chapter 5.4). Risk financing complements regulatory and economic instruments such as prices, taxes, tradable permits and liability. There is ample consensus that insurance can and should play an increasingly important role in mitigating disaster impacts, not only through risk sharing, but also by improving risk identification and modelling, risk awareness and recovery.

5.1 Prevention and mitigation: avoiding and reducing the new and existing risks

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5.1.1 Introduction

In line with the United Nations Office for Disaster Risk Reduction (UNISDR) definitions used in this report, prevention is understood as the activities and measures to avoid existing and new disaster risks (UNISDR, 2007). Prevention (i.e. disaster prevention) expresses the concept and intention to completely avoid potential adverse impacts of hazardous events. While certain disaster risks cannot be eliminated, prevention aims at reducing vulnerability and exposure in such contexts where, as a result, the risk of disaster is removed. Examples include dams or embankments that eliminate flood risks, land-use regulations that do not permit any settlement in high-risk zones, seismic engineering designs that ensure the survival and function of a critical building in any likely earthquake and immunisation against vaccine-preventable diseases. Prevention measures can also be taken during or after a hazardous event or disaster to prevent secondary hazards or their consequences, such as measures to prevent the contamination of water (UNISDR, 2016).

Ex ante interventions aimed at reducing existing risk (mitigation) and avoiding a generation of new ones (prevention) are important elements in the DRM process.

Mitigation relates to 'the lessening or limitation of the adverse impacts of a hazardous event. The adverse impacts of hazards, in particular natural hazards, often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions. Mitigation measures include engineering techniques and hazard-resistant construction as well as improved environmental and social policies and public awareness. It should be noted that, in climate change policy, 'mitigation' is defined differently and is the term used for the reduction of greenhouse gas emissions, which are the source of climate change (UNISDR, 2016).

The SFDRR, adopted by the United Nations General Assembly, calls for 'a culture of prevention' and enhanced risk reduction. Priority 3 of the framework focuses on 'investing in disaster risk reduction for resilience' and proposing 'public and private investment in disaster risk prevention and reduction through structural and non-structural measures are essential to enhance the economic, social, health and cultural resilience of persons, communities, countries and their assets, as well as the environment' (UNISDR, 2015). The Sendai framework provides a set of guiding principles relevant for any efforts aimed at addressing rising disaster risks, from global to local levels.

This subchapter explores current institutions, policies and challenges for disaster prevention and mitigation in Europe across different hazards. We differentiate between structural and and non-structural measures as well as examine the political complexities and barriers that currently hinder mitigation and prevention efforts. We then look at the economics of investing in mitigation and prevention, considering how the costs and benefits of different strategies and measures could be weighed up and compared. The section concludes with a reflection on how mitigation and prevention goals can be supported.

Development of the concept and use of DRM

In this subchapter we focus primarily on the institutions, policies, incentives and applications of mitigation and prevention measures as the principle ex ante actions used to manage risk. The concept of DRM has been developed in the context of managing risk related to natural hazards.

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The gradual adoption of DRM as a name and a framework for dealing with disasters has brought with it the realisation that natural hazards can only be managed effectively at the local level. The theatre of operations for both mitigation and response is inevitably local, although no one would deny the need for coordination at the regional and national levels of public administration, if not also the international level. The system that arises out of concerted responses to hazard can be termed civil protection. Its counterpart is civil defence, a nationally organised system that nowadays is heavily orientated towards threat management and counter-terrorism (Alexander, 2011). The factor that links the two approaches is vulnerability. In threat management, it is seen as the defence of weak points in the human socioeconomic system, whilst in civil protection, it is regarded as a systemic factor that is socially constructed because it reflects decision-making in all realms: physical, social, economic, institutional, environmental and so on.

Disaster impacts can be instantaneous, rapid, stepwise, ramped, 'creeping' (i.e. insidious) or of long onset. Although it is tempting to classify impacts by their causes into natural, technological, social and intentional, very many disasters are composite in nature. Such is the complexity of modern society and its interrelations that this has become the age of the cascading disaster. Impacts are propagated through critical infrastructure (CI) failures, with escalation points that mark the interactions between factors that generate positive feedback and spread the impacts into new areas (Pescaroli and Alexander, 2016). Several basic principles underpin effective risk mitigation and prevention. First, the underlying risk drivers need to be tackled. This means reduction in poverty and underdevelopment, as these are barriers to the protection of communities against hazards. We may add climate change abatement, redistribution of wealth and reinforcement of rights, including access to information, self-determination and freedom to act.

Secondly, a multihazard approach to planning is favoured because it is more efficient than a single-hazards approach. Vulnerability should be considered the essence of disaster risk, and hazard the trigger. Hence, abatement of vulnerability is the primary need in disaster risk reduction. Vulnerability to disaster can be considered by sector (economic, environmental, institutional, physical, etc.), but this runs the risk of failing to embrace the connections between sectors. An alternative approach might consider vulnerability to be pristine (unaffected by mitigation and prevention), technocratic (resulting from the misapplication of technology), wilful (the result of corruption and exploitation), economic (deficiencies in livelihoods) or socio-psychological (oppression, community conflict, etc.). It is essential to recognise that there is a constant dialectic between forces that create vulnerability and those that reduce it (McEntire, 2001).

Academic studies of the social impact of disasters have been carried out systematically for about a century. In the latter part of the 20th century and the beginning of the 21st, the field grew at an accelerating rate. As a result, it is now a rich repository of lessons to inspire future efforts in prevention and mitigation, if the lessons are learnt.

5.1.2 EU structures, institutions, strategies and political instruments

In recent years, the EU has taken an active role in drawing together the collective expertise of its members for the purposes of disaster prevention and mitigation (see Chapter 1). The European Commission (JRC) has been a central coordination mechanism in this endeavour. It developed the European Flood Alert System (EFAS) in 2003, providing local water authorities with probabilistic flood forecasting for transnational European river basins (Thielen et al., 2009). It also helped to establish the European Drought Observatory, which since 2011 has been the 'leading disseminator on drought-related information' such as precipitation measurements and soil moisture content (Stein et al., 2016). Another significant resource is the European Forest Fire Information System (EFFIS), which combines information from across European, Middle Eastern and North African regions, including fire danger assessments, damage assessments and a fire news module (JRC, 2015).

In addition to working with the national authorities of Member States, the EU also works closely with other independent organisations to improve the level of research and publicly available information on disasters. One such organisation is the European Exchange Circle on Flood Mapping, which produced a comprehensive handbook of good practices in flood mapping in 2007 (EXCIMAP, 2007). The EU also has an agreement with the European-Mediterranean Seismological Centre to monitor seismological activity and provide early notifications for earthquakes (Papatheodorou et al., 2014). Additionally, progress has been made with regard to multihazard disaster risk prevention and mitigation. Meteoalarm, developed by the European Meteorological Services Network, is a collaborative platform providing 24-48-hour lead-time warnings for extreme weather events in participating European countries (Alfieri et al., 2012).

In recent years, the EU has taken an active role in drawing together the collective expertise of its members for the purposes of disaster prevention and mitigation.

These partnerships are frequently underpinned by EU directives and policies, which provide the impetus and strategic vision for their work. Examples include the Water Framework Directive (2000), which established an integrated EU-wide framework for water management (Stein et al., 2016) and monitoring to address the problem of water scarcity and drought affecting many European countries (Quevauviller and Gemmer 2015). The issue of water scarcity and drought was later taken up as a main priority during the Portuguese Presidency in 2007, culminating in a formal communication by the European Commission on this topic (Stein et al., 2016). Other examples include the Flood Directive (2007), which aimed to standardise the level of flood protection that European citizens receive by prompting states to review their risk assessment policies and take deliberate steps to reduce flood risk (Alfieri et al., 2012). In April 2013 the European Commission also adopted an EU strategy on climate change adaptation to support adaptation planning and policies at all levels (Quevauviller and Gemmer, 2015).

These mechanisms and policies are, to a large extent, the result of broader commitments by the EU to protect civilian populations from disasters both within Europe and worldwide. The European Union Civil Protection Mechanism (UCPM), for instance, was established in 2001 to harness cooperation between the national civil protection authorities from all 28 Member States to respond quickly to civilian emergencies and assist in prevention and mitigation by allowing information sharing between countries.

In many EU countries, different hazards are still handled by different organisations and ministry lines, particularly in the prevention and mitigation phases. However, the methodologies, tools (e.g. EWS) and data are often common across many hazards (e.g. both land use planning and weather forecasts are crucial for floods, landslides, hurricanes as well as for drought and wildfires). Effective coordination mechanisms, such as the national platforms promoted by the SFDRR, are aimed at ensuring a joined-up understanding of risks, including the cascade effects of hazards, as well as coordinated resource allocation and integration of roles and responsibilities. The EU has adopted the SFDRR and developed an action plan accordingly (European Commission, 2016a).

5.1.3 Structural and non-structural measures and innovation in Europe

A common distinction is made between structural and non-structural measures. Structural measures are commonly derived from the engineering and physical sciences and include the following (Coppola, 2015):

- building resistant structures, such as dams and sea walls;
- using certain materials in buildings and adopting building codes that require structures to be disaster-resistant;
- relocating populations to safer areas;
- modifying the natural environment, such as slope terracing and draining.

Non-structural measures are generally described as 'soft methods' (Palliyaguru et al. 2014), or man adapting to nature (Coppola 2015). These may include the following:

- adopting regulations designed to prevent people from engaging in risky behaviour (for example, zoning laws);
- community initiatives such as flood warning systems (although these are usually classified as preparedness measures);
- modifying the natural environment without causing a structural change to it (for example, controlled burning of bushland to prevent bushfires);
- encouraging people to change their behaviour, such as providing tax incentives to plant trees.

Although most EU Member States implement mitigation measures at the national or local level, the European Commission will co-finance projects that enhance mitigation and preparedness through an annual call for proposals under the UCPM (European Commission, 2016b). In 2016, its total budget for assisting EU Member States was EUR 29 366 000 (European Commission, 2016c). This represents a slight increase from 2015, where the total budget was EUR 28 068 000.

Only a small percentage of this budget, however, is available for prevention and mitigation. In 2016, EUR 2.8 million was available for co-financing prevention projects (European Commission 2016c) and this amount did not increase from 2015. By comparison, EUR 5 million was made available for training EU civil protection teams and EUR 3.6 million was made available for planning, conducting and evaluating disaster simulation exercises (European Commission 2016c). Furthermore, although the maximum co-funding rate for a project is high (75 % of a project's cost), it only applies up to a maximum of EUR 800 000 for each project that is co-financed (European Commission, 2016c).

The list of projects that were co-financed in 2015 shows a focus on non-structural measures and improving response capability. This is in response to the clear domination of structural measures across the EU. The emphasis on non-structural measures by the UCPM can be seen as an attempt to balance the structural measures taken at the national level with non-structural assistance at the regional level. Supported projects include the following:

- improving evacuation preparedness in Romania and Slovenia in case of a nuclear accident (non-structural);
- improving knowledge against seismic risk through the KnowRISK project (non-structural);
- improving the capacity for addressing the impact of natural disasters on cultural heritage (non-structural); and
- a programme for improving the self-help capabilities of young people in times of disaster (non-structural).

Ex ante disaster mitigation and prevention can be achieved through a range of structural (e.g. building codes and their enforcement and structural protection measures) and non-structural (e.g. land-use planning and zoning) measures.

Technological innovation is recognised by the SFDRR as an important part of the arsenal available for reducing a society's disaster risk. In Europe, technological innovation is promoted in a number of ways, including but not limited to the following:

- The European Commission (JRC) has researched and produced a number of technological advancements (particularly computer-based systems) that have contributed to minimising the impacts of disasters on a global scale (JRC, 2014). For example, The European Commission (JRC) has conducted research on the vulnerability of buildings to seismic activity through its experimental reaction wall, which has also been used in other projects (e.g. the Series project) to test retrofitting techniques (JRC, 2014).

- The European Commission (JRC) also operates the European Crisis Management Laboratory for the development of information and communications technology as well as annual workshops addressing bespoke technological issues such as the use of unmanned aerial vehicles for rapid mapping (JRC, 2016). It used such vehicles to support the post-disaster needs assessment (PDNA) mission in Bosnia following the May floods in 2014 (JRC, 2014). The laboratory forms part of the Disaster Risk Management Knowledge Centre's 'innovation' stream, which also includes the European Network for Innovation Test Beds (DRMKC, 2016a). The innovation stream is focused on 'advancing technologies and capacities in disaster risk and crisis management' (DRMKC, 2016b).

- Horizon 2020, the largest EU research and innovation programme ever (European Commission 2016d), provides funding for projects improving societal resilience against natural and man-made disasters. These calls are made under its 'secure societies' stream. The following are examples of projects that have received funding and relate to DRR:

    1. The Brigaid project, which seeks to 'bridge the gap for innovations in disaster resilience' by providing a platform for the testing of resilience innovations (TU Delft, 2016). The EU contributed approximately EUR 7.7 million to the project (CORDIS, 2016a).

    2. The Liquefact project, which seeks to address the effects of earthquake-induced liquefaction disasters (CORDIS, 2016b).

Data innovations are increasingly supporting decision-making on mitigation measures at the national level. In the United Kingdom, for example, the Department for Environment, Food and Rural Affairs (EFRA) will be making greater use of crowdsourced data on regional flood risk thanks to improvements in data technology (UK Space Agency 2016). Further, innovation is also coming from areas outside the EU; for example, innovators seeking to provide technology solutions to mitigation regularly attend the annual Geneva-based International Exhibition of Innovations (Fowler, 2015).

5.1.4 Identifying appropriate prevention and mitigation measures

Risk assessment plays an important part for prevention and mitigation strategies, for example through applying risk information in decision support, evaluation and cost-benefit analysis (CBA) processes (Watkiss et al., 2014). Mitigation and prevention measures seem more likely to be adopted when an effective information-sharing programme is in place. For example, the EU seeks to foster the development of mitigation and prevention measures across different countries by reviewing their risk assessments and promoting best practice. Since 2012, eight such peer reviews have occurred across Europe (European Commission 2016b). Indeed, the EU has issued guidance for other states on how to prepare national risk assessments as part of the UCPM (European Commission, 2016b). Risk information also plays an important role in assessing the appropriateness of risk management activities/strategies in anticipation of future risk conditions. Information requirements about risk and the kind of risk assessment applied may differ depending on the needs of the decision-maker (Surminski et al., 2012).

In Europe, FP7-funded ENHANCE project has shown that the kind and scale of a risk assessment depend on how the results are used by decision-makers. For example, the EU-wide flood risk assessment informs the design of the EU solidarity fund, while the local assessments of surface water flooding in the United Kingdom and drought risk in the Jucar provide useful information for local risk management policies, such as insurance and water pricing (Botzen et al., 2015).

In addition to risk information and data, mitigation and prevention measures require support and interaction between stakeholders, whether it be at the local, regional or international level. This includes public and private stakeholders. Engaging with communities at the local level can foster the adoption of risk-reduction techniques by individuals engaged in that community (Wittyorapong et al., 2015). This also requires a combination of both 'top-down' and 'bottom-up' strategies (European Commission, 2013). For example, utilising a 'bottom-up' approach, communities in the Pacific Islands have developed their own techniques to combat tropical hazards (e.g. cyclones). The implementation of these techniques is monitored by Red Cross volunteers, allowing the transition of information from the local to the international. This is referred to as 'participatory DRR' (European Commission, 2013).

Tools and models for understanding risk are well advanced within Europe and can be used as the basis for identifying and prioritising action to reduce risk and avoid risk creation in the future.

The recent emphasis on resilient cities is another example where action at the local level can inform international-level thinking. Carmin et al. (2013) present several examples of city-based, stakeholder engagement partnerships for supporting adaptation to climate change and resilience in diverse contexts, including large cities such as Toronto, Quito and London and smaller urban centres such as Walvis Bay in South Africa (Carmin et al., 2013). This coincides with the realisation that cities form a pivotal part in pursuing internationally agreed policy goals, including climate mitigation and adaptation, as well as DRR (Bulkeley and Castán Broto, 2013). Cities are of importance in managing climate risks as they serve as centres of economic activity, technology and innovation hubs while often being exposed to a range of climate risks, including potential infrastructure failure, urban blight and loss to both populations and assets (Surminski and Leck, 2016). Recent examples of initiatives that promote mitigation and prevention (Geneva Association, 2016; Golnaraghi et al., 2016) include city-level and industry collaboration.

- **Encouraging mitigation and prevention in urban areas**
  The UNISDR (n.d.) global campaign for resilient cities has focused on raising awareness about risks and comprehensive approaches to risk preparedness and reduction among local governments and authorities and urban communities. The 100 resilient cities initiative, launched by the Rockefeller Foundation, is supported by a number of international associations such as the International Consortium of Local Governments for Sustainability, other foundations (such as the Clinton Foundation), the United Nations and other non-governmental organisations (NGOs). It has been instrumental in raising awareness, sharing experiences and facilitating global cooperation among local governments to develop resilient cities based on seven key principles that allow them to withstand, respond to and adapt more readily to shocks and stresses. This initiative provides member cities with four types of support: assistance to develop a comprehensive 'resilience strategy'; access to a USD 100-million-plus (EUR 91.7-million-plus) pool of best-in-class services from partners in the private, public, NGO and academic sectors; and connection through a peer-to-peer network so that cities can learn from each other's success and failures. It also offers funding and support for hiring a chief resilience officer, a top-level advisor who reports directly to the city mayor. Their task is to establish a compelling resilience vision for their city, working across departments and with the local community to maximise innovation and minimise the impact of unforeseen events. To date, this initiative has led to the designation of chief resilience officers in 68 cities.

- **Collaboration with industry**
  In several countries the private sector is funding technical development as well as testing facilities for building materials, designs and techniques. In Germany the prevention and safety testing institute, VdS, was initially set up by insurers as a way to support fire resilience in businesses and industry. Insurers in the United Kingdom are collaborating with the Environment Agency (the government agency responsible for flood risk management) to provide guidance and information about flood resilience techniques to home owners. In France the insurance industry formed the Mission Risques Naturels association to foster disaster risk awareness and reduction activities across public and private stakeholders. Triggered by concerns about rising disaster loss, the Japanese insurer Tokio Marine is focusing on ecosystem-based solutions for DRR, or 'Eco-DRR.' As the United Nations environment programme

(UNEP) pointed out in its 2014 report, natural ecosystems, such as mangroves, can demonstrate physical and economic effectiveness in reducing the impact of storm surge or tsunami. The 8 994 hectares of mangroves in nine Asia-Pacific countries planted by the company since 1999 are being studied for the shelter effect and its consequential economic benefits so far generated to improve the living standard of the local inhabitants (Geneva Association, 2016).

If and how effective all these advances in risk information, knowledge sharing and technology are remains somewhat unclear. Moving towards implementation and changing existing behaviour in terms of home construction and building design requires a range of incentives as well as legislative support, for example through building codes (Surminski, 2014). Governments, organisations and people are not inherently interested in mitigating disasters unless they perceive a direct benefit, and greater effort is needed to draw attention to these benefits and to improving the incentives for investing in mitigation and prevention.

Furthermore, the effectiveness of mitigation and prevention measures must be weighed against, amongst other things, their social cost (Vorhies and Wilkinson, 2016).

5.1.5 The economics of mitigation and prevention

Economic analysis methods have been applied to gain a better understanding of the economic benefits of mitigation and prevention. Building a home on an elevated platform between 0.5 metres and 1.5 metres, for example, could reduce loss due to flooding by 10 % and 80 % below present-day levels in coastal areas, respectively, even in the context of a sea level rise that would otherwise increase the 1-in-200-year loss by 20 % (Lloyd's, 2008).

CBA is a popular and oft-advocated tool to choose between alternative DRM options. Ideally, it compares advantages (benefits) and disadvantages (costs) of options in a systematic and objective way, so that the option that provides the greatest net gain to society can be selected. The EU Floods Directive 2007/60/EC requires that flood risk management plans 'take into account relevant aspects such as costs and benefits' (European Union, 2007), and this has undoubtedly given an incentive to apply CBA in regions where it was not common before.

CBA has often been criticised, however, because it requires all costs and benefits to be expressed in a money metric to compare them, and that it is biased towards those options that can most easily be expressed in monetary terms, to the disadvantage of options that provide intangible benefits in the form of greater social or environmental quality (Vorhies, 2012). Yet the United Kingdom Foresight report, Reducing risks of future disasters (UK Government, 2012) argues that, especially in times of austerity, CBA continues to be an important tool for prioritising efficient DRM measures. However, with a shifting emphasis from infrastructure-based (hard) options to preparedness and systemic (soft) interventions, other tools such as cost-effectiveness analysis, multicriteria analysis and robust decision-making would deserve more attention (Mechler, 2016). In the context of adaptation to climate change, the Intergovernmental Panel on Climate Change of 2012 concluded for such reasons that the applicability of 'rigorous' CBA for evaluations of climate adaptation would be limited.

Mitigation and prevention measures are widely considered more cost-effective than ex post disaster interventions. This is predominantly based on an analysis of the benefits arising from avoided loss.

Recently, there has been a push towards studies taking a probabilistic approach for addressing disaster risk, particularly those arising from low-frequency, high-impact events. This is a promising development for two reasons: 1) disaster risk is probabilistic in 'nature', which means that looking at one flood event only does not capture the entire distribution of possible flood events and their respective return periods; and 2) DRR options are efficient for certain levels of risk but not necessarily for all; e.g. risk reduction is more effective for frequent events (up to 50- or 100-year return periods), while insurance tackles higher-level risk. Indirect ef-

BOX 5.1

Examples of using risk assessment for improving mitigation and prevention

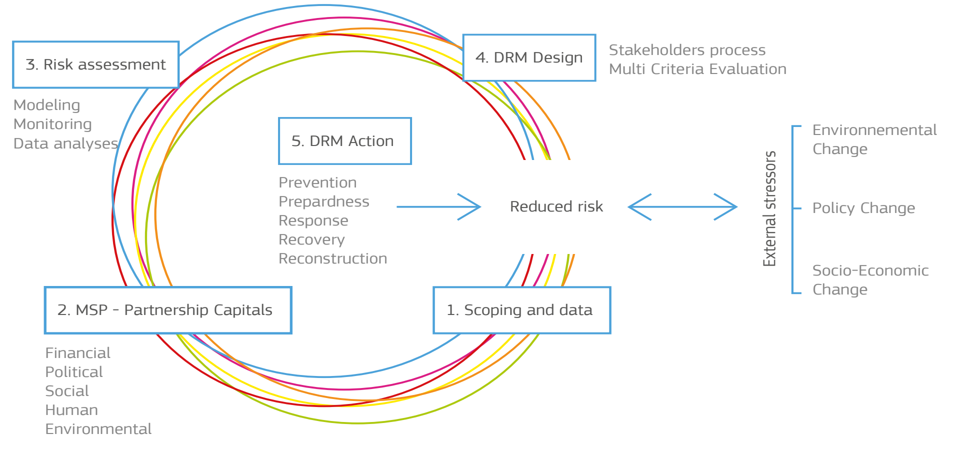
Risk assessment and information is key to any mitigation or prevention decision. Risk assessment looks to understand future permutations, constantly updating projections on risk scenarios through risk assessment and reflection (Tschakert and Dietrich 2010). The Enhance project has deployed a range of new risk scenarios and information in selected hazard cases in close collaboration with stakeholders. The project focusses on selected cases of high-profile catastrophic hazards in a variety of countries, including multihazard events (EU wide) as well heatwaves (EU wide), forest fires (Portugal), surface water flooding (United Kingdom, Italy and Romania), droughts (Spain and Italy), storm surges (Wadden Sea and Rotterdam), flash floods and landslides (Austria) and volcanic eruptions (Iceland with Europe-wide effects).

One example is surface water flood risk in London, United Kingdom. Through the Enhance project, the latest London flood risk analysis data was fed into an agent-based model (ABM), which is a useful method for understanding systems and individual behaviour. This ABM has been developed to demonstrate the effects of flood risk and mitigation and prevention measures on risk levels, household wealth, potential shifts in inequality caused by flood damage and insurance (un) availability (Jenkins et al., 2017).

Results of the ABM highlight how development of properties in certain areas can become unsustainable as well as how there is a need for a consistent framework between different stakeholders to promote flood risk reduction (Jenkins et al., 2015).

FIGURE 5.1

Setup of the ENHANCE framework for assessing the healthiness of MSPs, to assess current and future risk levels, and to reduce and manage risk through DRR design and action.
Source: Novel Multi Sectoral Partnerships. EU Enhance project. (Aerts and Mysiak, 2016)



fects (i.e. impacts on livelihoods and the local and regional economy) are being considered more strongly, while accounting for intangible effects, such as on health or impacts on natural resources, has remained a challenge.

Another important consideration is the data needs for calculating the net benefits of a measure. This requires information about the costs: both direct costs as well as opportunity costs of other investments or even other DRM measures. However, data on these indirect costs are not always readily available (Vorhies, 2012).

One further aspect is how to account for the benefits of any mitigation or prevention activities: at local or project level the benefits are directly linked to a certain location where the mitigation or prevention activity takes place, while at national level an aggregate, macroeconomic view is applied, considering the implications on economic growth, national employment, federal budgets or poverty-reduction efforts.

This distinction is important as a project may show the potential for benefits to a local area, while substitution effects may mean it does not show benefits nationally. For large countries, establishing impacts at a national level may prove difficult. Hence the usefulness and robustness of a CBA generally declines as time and scale increases (Mechler, 2008). Recognising and appraising the wider co-benefits might deliver an even more convincing case for mitigation and prevention. Table 5.2 highlights the range of co-benefits that can arise.

An interesting extension of the existing approaches to appraising mitigation and prevention measures is the 'triple resilience dividend' concept. It provides a much broader approach to appraising investment in DRR efforts, citing positive spillovers that even create economic gains in the absence of disasters (Tanner et al., 2015; Tanner and Surminski, 2016).

5.1.6 Policies, institutions and incentives for investing in mitigation and prevention

Exposure to hazards has increased faster than our vulnerability has decreased (UNISDR, 2015). Indeed, since the 1970s research has argued that disasters are manifestations of unresolved developmental problems because most hazards are constructed through the same processes (economic, social and territorial) that produce exposure and vulnerability (Lavell and Maskrey, 2014). In addition, there is growing economic evidence of the cost-effectiveness of many mitigation and prevention measures, particularly when compared to ex post disaster support.

However, this has not yet triggered a significant shift of political and financial focus away from ex post towards ex ante measures: although the European Commission estimates that every EUR 1 spent on DRR measures saves EUR 4 to EUR 7 (European Commission, 2016b), significantly more (indeed, up to 95 % of total funds) continues to be spent on post-disaster recovery (Aakre et al., 2010). Prevention and mitigation requires buy-in and action from across a variety of institutional bodies, political entities and stakeholders.

Understanding the incentives and disincentives to investment is key to the promotion of ex ante investment in mitigation and prevention. An expanding body of scientific evidence on the benefits of these investments can help improve the business case.

The literature provides a long list of barriers and challenges for a greater ex ante focus on mitigation and prevention, which Coppola (2015) summarises as financial, political, technical and sociocultural. In addition, effective prevention and mitigation requires community engagement across the entire suite of stakeholders, as it cannot be provided by any single authority or agency (Palliyaguru et al., 2014). Indeed, local communities tend to be the first responders to natural disasters and therefore might have valuable information about the best mitigation practices (Genovese and Przyluski, 2013). Similarly, the private sector, while dominating the financing and delivery of infrastructure investments, does not seem to be fully aligned with the prevention and mitigation principles when it comes to day-to-day business operations (UNISDR, 2013). Even the insurance industry views disaster prevention and mitigation as a domain of the state, which can be supported by private sector action, but only through better public/private collaboration (Surminski et al., 2015). Involving the private sector is particularly relevant in the context of infrastructure. The World Energy Council (2015) provides critical evidence on the impacts of extreme events and emerging risks associated with climate change on energy infrastructure and recommends that the industry work together with the financial community, investors and policymakers to share and promote measures that must be incorporated into energy infrastructure design and investment decisions (Golnaraghi et al., 2016).

A key to successful resilient partnerships between policymakers, private sector actors and scientists is a common understanding of the risks, preferences and needs of actors and the implications of proposed economic and regulatory policy instruments (National Research Council, 2011).

Successful examples of such resilient partnerships include the joint implementation of non-structural measures such as building codes (CEA, 2007). Several EU-funded projects, such as MOVE, Ensure, Conhaz, Matrix, Catalyst and emBRACE, have significantly advanced scientific knowledge and produced methodological innovations with respect to assessing and managing risk and exploring resilience to natural hazards. They have developed scenarios of risk for different natural hazards and have examined risk management measures and how the concept of resilience can be used to reduce the negative impacts of those hazards on society. As a result, resilience to natural hazards is becoming a more integral component of current policymaking and implementation, both at the country as well as at EU scale. This has also informed policy drivers, such as the EU Floods Directive, and to a lesser extent the EU Agricultural and Regional Policy.

Despite considerable disincentives to investing in prevention and mitigation, an increase in mitigation investment has occurred in some European countries (See Box 5.2 on seismic investment in Italy), but the lack of public and therefore political interest in prevention and mitigation remains a problem.

5.1.7 Achieving mitigation and prevention through land-use planning

TABLE 5.1

Benefit-cost ratios for a global review compared to a prominent United States study only (MMC, 2005)
Source: Mechler (2016)

Hazard	Review. Simple average (number of studies)	Review. Range of estimates	MMC (2005). Average
Flood (riverine and coastal)	4.6 (21)	0.1-30	5.0
Wind (tropical and extratropical)	2.6 (7)	0.05-50	3.9
Earthquake	3.0 (8)	0.08-15.6	1.5
Drought	2.2 (1)	1.3-2.2	na
Landslide	1.5 (2)	0.1-3.7	na
Overall	3.7 (39)	0.08-50	4.0

Human exposure to natural hazards risk is mainly caused by settlement and other economic developments in hazard-prone areas. For example, many large urban centres are located in low-lying floodplains prone to floods and storm surges (Jongman et al., 2012) and in earthquake zones (Daniell et al., 2011). The reason for developments in hazard-prone areas is often the economic attractiveness of these locations. For example, port cities in low-lying coastal areas are historically centres of economic activity and therefore attractive for urban development, despite being vulnerable to storm surges (e.g. Brown et al., 2014). In the case of mountainous areas, valleys are the only suitable areas for urban development and form the economic basis for tourism development, although they are threatened by landslides and avalanches.

The question that arises is how to develop these areas so that vulnerability to natural hazards is managed in a way that it limits risks to human life, physical structures and the economy in general? Protection measures, such as levees and avalanche shields, are mainly targeted to limiting the magnitude and probability of hazards. In addition, measures can be developed that lower exposure and vulnerability. With respect to the latter two, spatial planning policies and regulations play an important role as they determine where and how people and economic assets will be located (King et al., 2016). Hence, spatial planning directly influences the exposure of people and economic assets as well as how vulnerable these exposed assets and people are (Greiving et al., 2006). During the last 10-15 years, there has been increasing attention within spatial planning policy to address the is-

TABLE 5.2

The range of co-benefits associated with DRM measures
Source: adapted from the Environmental Resources Management and the Department for International Development (2005)

DRM activity	Possible co-benefits
Flood protection structures	Provision of irrigation or potable water and hydro-electric power Dual-purpose road infrastructure
Strengthening DRM capacity of civil society	Improved governance, more organised social structures
Ecosystem-based DRM approaches	Environmental conservation, improved air quality, climate change mitigation
Shelters	Community facilities (e.g. clinics or schools) in non-disaster periods
Improving water supply systems in rural areas	Water supply systems improved regardless of a disaster occurring
Construction and use of drainage pipes, canals and water retention basins	Improved irrigation practices, possibly improved agricultural practices Dual purpose road tunnel or parking lot infrastructure
Community-based disaster preparedness	Improved women's involvement in community-level activities
Installing more resilient wireless communications	Enhanced access to telephony and electronic data services
Training farmers to diversify the use of crops	Reduced vulnerability to poverty
Better monitoring of food supplies	Improvement to the food supply chain, possibly making it more cost-effective

BOX 5.2

The Italian national seismic prevention programme

Over the last 50 years, earthquakes with a magnitude between 5.5 and 6.9 in Italy have resulted in thousands of victims and monetary losses of over EUR 160 billion. Even considering the present condition of the building stock and the possible occurrence of future earthquakes, expected direct costs are of the order of EUR 2-4 billion per year.

Similar to other countries subject to seismic hazard with high population exposure and high vulnerability of constructions, a huge effort would be needed to mitigate seismic risk, which requires different and parallel lines of action to be pursued: the improvement of the knowledge, the reduction of the vulnerability and exposure and the mitigation of the effects. Seismic prevention remains, however, a difficult objective to achieve fully due to the high costs implied, long time frame and lack of public and political interest.

After a destructive earthquake, some seismic risk mitigation measures are usually taken, mainly consisting of the improvement of seismic codes and classification, but with little economic effort to directly reduce vulnerability in areas not affected by that earthquake.

In Italy, since 1986 very few investments have been made in structural seismic prevention, and almost exclusively on strategic and important public buildings (hospitals, schools, etc.). A change of perspective occurred after the earthquake on 6 April 2009 in Abruzzo. Two articles of Law 77/2009, issued for reconstruction in the damaged areas, have instead been devoted to seismic prevention in the entire nationalterritory.

Article 1bis established the immediate enforcement of the new technical standards promulgated at the beginning of 2008, but not fully enforced yet, while Article 11 allocated around EUR 1 billion for seismic prevention, to be spent in the following 7 years. This is a small fraction of what is needed to solve the problem of seismic risk in Italy and less than half the expected average annual cost of earthquakes. Nevertheless, Italy now has a national seismic prevention programme and EUR 965 million has been spent in 7 years on reducing seismic risk.

The National Seismic Prevention Program essentially focuses on the following points:

- Reducing the risk of human loss rather than economical loss, especially for private buildings.
- Stimulating the attention of private owners and administrators towards the different problems of seismic risk (vulnerability of buildings, importance of local amplification and co-seismic effects and use of microzonation studies to improve urban and emergency planning and correct implementation of civil protection plans considering the vulnerability of the strategic elements and of the interconnection routes).
- Seeking co-funding by local public administration and by private owners to at least duplicate the actual effects of the allocated fund of the state. At present, the funding programme is approaching its end. The evaluation of the results provides some positive feedback, but also emphasises some difficulties that are related to the spending capability of local administrations.

This experience confirms that a prevention programme has to be based on a strong scientific background and developed through a long time horizon, so that public administrators and private owners can adequately make their prevention plans and put them in effect.

Source: Dolce (2012)

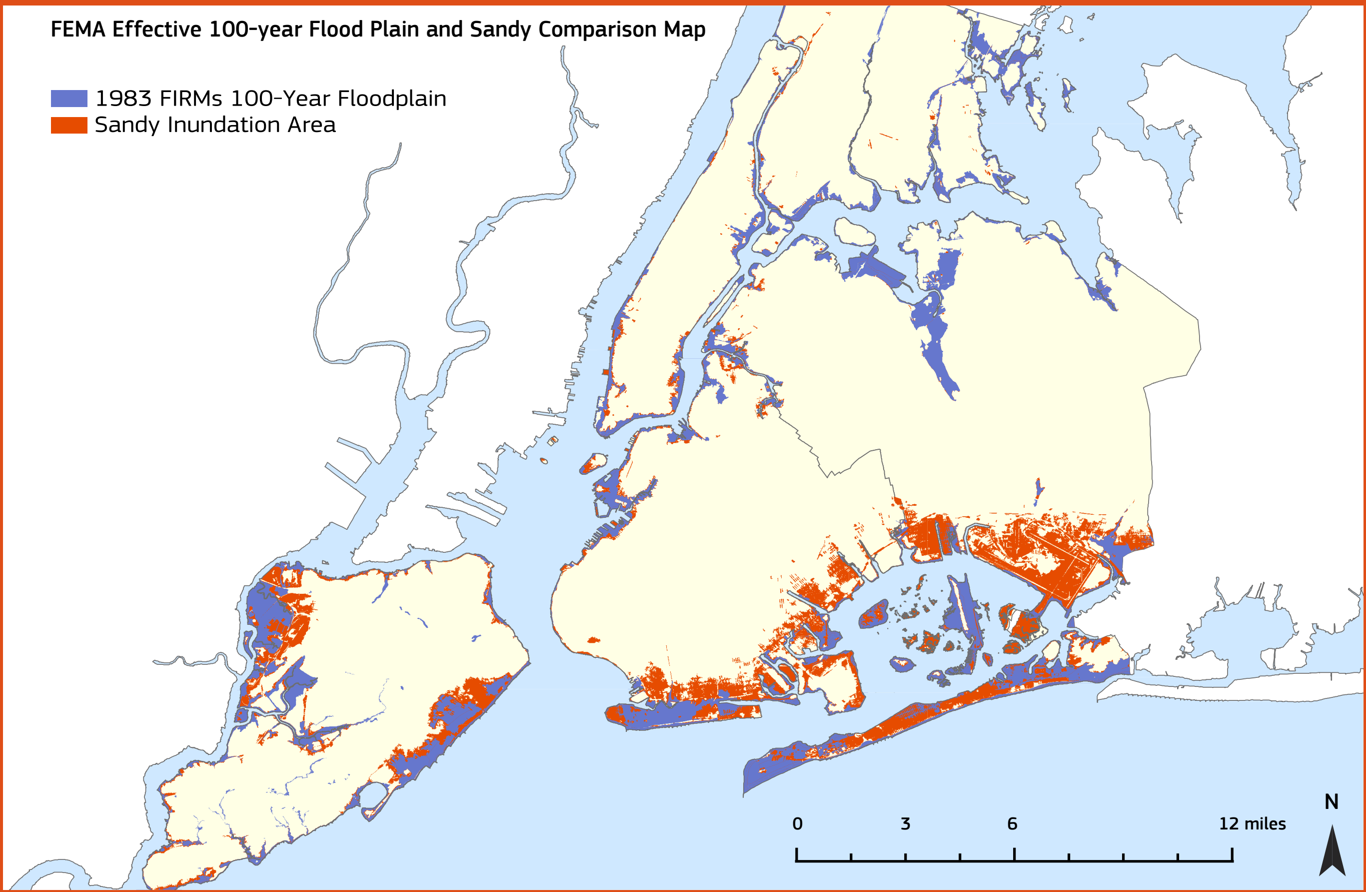
BOX 5.3

Importance of risk assessment for land use

Where inaccurate risk information can lead to is exemplified in the Figure 5.2. This figure shows a map of New York City for the actual flooding due to Hurricane Sandy in 2012 (in red) and the official 1/100 flood zone (in blue) provided by the government before the hurricane occurred. The figure shows that many of the actual flooded areas are outside the official flood zone. Inaccurate perception of flood risk for an area may lead to the development of urban areas in unprotected areas or to under-designing levees for protecting people against extreme events.

FIGURE 5.2

New York City – a comparison of the actual flooding due to Hurricane Sandy in 2012 (in red) and the official 1/100 flood zone (in blue) provided by the government before the hurricane occurred.
Source: Aerts and Mysiak (2016)



sue of disaster prevention, but there is still a need to further integrate risk assessment within spatial planning processes; this has been advocated by the SFDRR (Mysiak et al., 2015).

5.1.7.1 National Policies

Spatial planning involves different scales of policy- and decision-making. Regulations at the national and even continental scales (such as the EU) prioritise the importance of the use of space for different land uses and, for example, lay out what areas should be protected from further development (e.g. national parks; Natura 2000 sites; e.g. Mikkonen and Moilanen, 2013). Spatial planning policies at the highest levels also set out guidelines and benchmarks for safety against natural hazards. As an example, although not directly targeted at natural hazards, the EU Seveso III directive (European Union, 2012) states that 'Member States shall ensure that the objectives of preventing major accidents through hazards and limiting the consequences of such accidents for human health and the environment are taken into account in their land-use policies or other relevant policies'. In addition, the EU Flood Directive (European Comission, 2007) aims at reducing flood risk by encouraging cross-border integrated flood risk management plans for all European river basins. These plans should cover all aspects of flood risk management, integrating spatial planning policies and physical-hydrological measures such as protection and preparedness, including flood forecasts and early warning. These policies include making sure that the siting of new transport lines and the development of new buildings or modifications of new establishments must address risk from hazards.

Human exposure to natural hazards risk is mainly caused by settlement and other economic developments in hazard-prone areas. This risk can be reduced through spatial planning and regulations that should take into consideration opportunities for economic growth, development of communities and well-being.

National policies often involve cooperation with other countries within river basins. An example is the flood retention areas in the Rhine basin, which aim at storing flood waters upstream in Germany to reduce the risk of flooding downstream into the Netherlands. These retention measures use space, which has to be reserved, or require land-use change to create space (Te Linde et al., 2010). Another example is the efforts in Germany after the 20o2 floods. These floods showed that retention areas that can be flooded in a controlled manner can be effective. In addition, floodplain surface in Germany has been reduced by one third, and policies were developed to further install retention areas through reserving space in spatial planning policies to bring back resilience to floods in the hydrological system (Thieken et al., 2016).

Since the basis for prevention and mitigation is the availability of accurate risk data, national policy within the spatial planning domain plays an important role in initiating risk mapping activities to assess areas that are at risk from natural hazards. Risk maps can be used to prioritise land-use planning, to restrict development in some high-risk areas or to impose additional measures in areas above certain risk thresholds to lower vulnerability.

For flood risk management, this process has been geared up in the EU through the EU floods directive (European Comission, 2007). This directive requires Member States to assess flood risk by developing spatial flood risk maps (De Moel et al., 2008) and to prepare catchment-based Flood Risk Management Plans (FRMPs), that include spatial planning actions and measures (Office of Public Works, 2009). Flood risk maps must show information on the flood extent, water depths/level and flow velocities. On the basis of these maps, Member States are to develop flood risk management plans aiming at the 'reduction of potential adverse consequences of flooding for human health, the environment, cultural heritage and economic activity, and, if considered appropriate, on non-structural initiatives and/or on the reduction of the likelihood of flooding' (Van Rijswick and Havekes, 2012).

Another opportunity to include disaster risk in spatial planning processes stimulated at the national scale is to further integrate risk assessments in Environmental Impact Assessment (EIA), which is a procedure that ensures that the environmental implications of decisions are taken into account before decisions are made. In principle, it can be undertaken for individual projects such as the development of a new airport or for plans and programmes (Strategic Environmental Assessment - SEA). An example for SEA includes the assessment of a regional spatial plan in which risks from natural hazards are ideally considered (Greiving et al., 2006). The recent EU Environmental Impact Assessment directive has acknowledged the need for greater integration of risk information in this kind of assessment (European Union, 2011).

5.1.7.2 Zoning

At the regional to local scales, national DRM guidelines and policies are commonly elaborated in zoning- and building-code policies. Zoning regulations are set to control land use and setting development standards throughout urban areas. Zoning makes it possible to create transitional land-use patterns so that incompatible uses are separated and buffered. Zoning regulations determine what land can be used for, or combinations of use for available space, and what kinds of buildings can be developed, including how they address natural hazard risk management. In terms of utilising space for especially urban areas, zoning policies and building codes are powerful tools for controlling land use and urban development, and hence (changes in) future land use (Burby et al., 2000). As such, zoning is increasingly seen as an important tool in climate adaptation and managing changes in natural extremes due to climate change (Aerts and Botzen, 2011).

Zoning encompasses the following general policies related to urban development and risk management:

- Restrictions: based on hazard maps and/or additional risk information (See Box 5.3), zoning policies may indicate that in certain areas urban development is not allowed.

- Conditional development: urban development is allowed in risky areas, but only when certain conditions are met, for example by:
  a. implementing building codes;
  b. homeowners have purchased insurance against natural hazard risk;
  c. buffer zones are respected, whereby building development is only allowed when appropriate distances between establishments and vulnerable risk areas are maintained.

Zoning and land-use planning is also used to create space for other risk management measures, for example by creating structural space for escape lanes (e.g. in case of flooding) or by providing space for structural measures such as dikes, avalanche protection or forest protection against landslides (e.g. Dorren et al., 2004).

In special cases, spatial planners may decide to 'retreat' or relocate the inhabitants of an area. Such rare cases exist, for example in the aftermath of extreme events (e.g. the Tsunami events of 2004 and 2011), when the costs of rebuilding an area elsewhere are lower than rebuilding urban settlements on original (but devastated) land. In addition, inhabitants who have been evacuated from the disaster area do not want to return to their previous living area because they have found a home elsewhere or because reconstruction takes too long (Ranghieri and Ishwatari, 2014). Retreat, as an alternative option to lower exposure without having had a disaster, is rarely considered a feasible option for policymakers. Only few examples are known where people have moved voluntarily to another location; an example is the creation of an extension of a floodplain in the Netherlands (Schut et al., 2010). People were compensated either to leave the area, or were subsidised to elevate their homes a few metres, which in practice meant completely rebuilding their homes. Although the area only comprised some 30-40 households, it took more than 15 years to develop and implement the project. Some authors, however, argue that sea level rise will initiate an increase in relocation of low-lying urban centres near floodplains and coastal waters (Hauer et al., 2016). Again, politics here is important.

5.1.7.3 Object level and building codes

Zoning regulations, and in particular zoning for conditional development, can be further refined in building codes regulations for the development and maintenance of buildings in risk zones. Building codes are meant for the adaptation of building structures to lower their vulnerability to natural hazards. Building codes are anchored in planning law, which is operationalised in legally binding land-use or zoning plans. These zoning plans lay out the areas where building codes will be enforced.

Specific measures to comply with building codes pertain to different hazards. For example, in the United States, buildings that lie in flood-prone areas need to elevate their base floor to a minimum height. Flood zones are mapped by the Federal Emergency Management Agency (FEMA) as Flood Insurance Rate Maps (FIRM), representing the 1/100 flood zone. In these flood zones, building codes apply and homeowners need to seal basements or crawlspaces to avoid the entrance of flood waters. Furthermore, electric facilities (sockets and heating systems) must be installed above certain elevations to avoid power outages and short circuits (Aerts and Botzen, 2011).

A study by De Moel et al. (2014) in the port area of the City of Rotterdam in the Netherlands shows that the current flood risk is about EUR 40 million per year. A large part of this risk can be attributed to industrial land use. Climate change and sea level rise may double the risk by 2100 if no additional measures are implemented. The research showed that by dry proofing all buildings in the port area by up to 1 m, risk would be reduced by 56 %. Elevating all buildings by only 0.5 metre would reduce the total flood risk by 50 % (De Moel et al., 2014).

Building codes for earthquakes may involve specific requirements to improve the seismic resistance of buildings. For example, the National Earthquake Hazards Reduction Program (NEHRP) in the United States shows how to design and construct practices that address the earthquake hazard and minimise the resulting risk to life and property (FEMA, 2009). For landslides, building codes focus on reinforcing walls and list specific requirements for the groundwork of the building (see, for example, the handbook of the Australian Building Codes Board on landslides, ABCB, 2015). Under Eurocodes, the EU standard for construction, structural design rules are laid out for seismic-resistant structures as well as resistance to hydrometeorological hazards, often replacing the national codes.

In some countries, zoning regulations, building codes and insurance policies are integrated. For example, in the United States, homeowners can buy flood insurance when their property complies with the prescribed building codes. Homeowners may even derive a discount on their flood insurance premium when they implement more stringent measures via a Community Rating Program (CRS) to lower vulnerability (see Aerts and Botzen, 2011). Building codes and zoning measures, however, also take quite some time to develop and to process them through all regulatory bodies. In many instances, building codes are not yet assessed against increases in risk through, for example, climate change (see Burby, 2006).

5.1.8 Conclusions and key messages

Partnership

National DRM policies increasingly involve cooperation with other countries. Within cross-boundary river basins, countries can jointly seek policies to control flood waters, for example, through spatial planning. Partnership for mitigation and prevention is particularly important in urban areas because of the disconnect between national and local responsibilities and resources. Horizontal city-to-city knowledge sharing and technology transfer is invaluable because of the unique context of urban systems. Resilience strategies can bring in the private, public, NGO and academic sectors.

Knowledge

However, identifying suitable investments is not enough. Presenting evidence of additional dividends to policymakers and investors could provide a narrative reconciling short- and long-term objectives. This will improve the acceptability and feasibility of DRM investments, enhancing the business case for investment in prevention and mitigation.

Innovation

Integration of policies and regulations across sectors such as zoning regulations, building codes and insurance policies would be a key innovation in mitigation and prevention, making the mitigation strategy more coherent and easier for stakeholders to implement.

5.2 Preparedness and response

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5.2.1 Policy and institutional architecture of preparedness and response in Europe

The DRM policy landscape has transitioned to 'civil protection', emphasising the importance of effective transboundary coordination and cooperation to manage transboundary disasters. This has been accompanied by a shift towards the role of policy in adaptive management and in protecting the rights of victims and survivors. Science plays an important role in better understanding the complexity of modern disasters and in devising suitable tools and approaches for preparedness and response.

5.2.1.1 Policy landscape and trends

Historically within European states, disasters were times when affected individuals had to self-organise, as external response was not systematically available, if at all. This changed in the 20th century when states started to organise loose structures of ordinary citizens intended to respond in times of crisis. For fires, this concept dates back to the Romans (Goudsblom, 2015). In recent history, the risk of aerial bombing across Europe led to a significant shift with the formation of civil defence organisations (Dynes, 1994; Van der Boom, 2000). By a decade or so after the Second World War, a transition had taken place from an essentially untrained volunteer-based response system to disaster management organisations staffed by paid professionals. Most European countries moved towards a professionalisation of disaster management and a centralised command-and-control structure (Dynes, 1994).

Command and control through civil defence centred on managing populations in the face of aggression and on emphasising top-down methods (Alexander, 2002). During the Cold War (1948-1989), the focus on possible relocation of civilian populations under threat of nuclear attack saw civil defence administered by military and paramilitary groups. Scientific critiques of civil defence point to the possibility for such institutions to become an instrument of repression and used to 'protect the state against its people' (Alexander, 2002).

Science played a key role in shaping the nature of civil protection.

Science played a key role in shaping the nature of civil protection through the 1960s to 2000s. Research questioned the role of the military in emergency management and helped to shape the non-military, civilian character of emergency preparedness that emerged (Alexander, 2002). A better understanding of the complexity of modern disasters has focused attention on adaptive emergency management as well as the rights of victims and survivors. The military still has a role to play; in redefining its role in disaster preparedness and response, military forces can be used in integrated ways with civil protection, or civil protection forces may contain pseudo-military organisations. For example, some fire brigades are partly organised along military lines, and non-governmental organisations such as the Salvation Army adopts a pseudo-military image (Alexander, 2002). Overall, 'modern civil protection is not inherently authoritarian' (Alexander, 2002), although the 11 September 2001 terrorist attacks altered emergency planning with a new focus on terrorist incidents and response operations in which police force or military units would usually be the lead agency (Alexander, 2002). Concerns over the possible remilitarising of civil protection in light of efforts to prepare for possible terrorist attacks are regarded as a threat to progress made in the 2000s in expanding civilian disaster response networks (Alexander, 2002).

5.2.1.2 Institutional architecture and coordinating mechanisms

European Union members have over time been drawn closer together by policies and legislation facilitating greater interstate cooperation (Boin et al. 2014b). The risks facing Member States have become increasingly

BOX 5.4

European Union Civil Protection Mechanism

When activated, the mechanism provides support via the ERCC, which provides 24/7 capacity to monitor and coordinate response to disasters. It is directly linked with the civil protection and humanitarian aid authorities in the participating states.

The centre also acts as the central 24/7 contact point in the eventuality that a Member State activates the solidarity clause (Article 222 of the Treaty on the Functioning of the European Union) or when the European Union presidency activates the integrated political crisis response arrangements and ensures coordination with other EU services and bodies for the response (ECHO, 2016).

Recent disasters such as the western Balkans flooding (2014), the eastern Ukraine conflict (2015), the forest fires in Greece (2015) and the European refugee crisis (2015-2016) have activated the mechanism and therefore the ERCC. Twenty-eight Member States plus a number of other European countries participate, providing additional response capabilities in times when the disaster exceeds those of the state in which the crisis takes place. Assistance deployed includes technical expertise, relief and equipment items, as well as advice on preparedness measures.

In 2013, legislative changes placed greater emphasis on preparedness (through the mechanism), including the establishment of a voluntary pool of pre-committed response capacities. In addition, EU funding helps address caps and temporary shortcomings in preparedness and response planning, including 'improving the quality of and accessibility to disaster information, implementation of prevention measures, raising of public awareness of risks and disaster management, supporting Member States in risk assessment and hazard mapping based on guidelines, encouraging research to promote disaster resilience and reinforcing early warning tools' (ECHO, 2016).

Source: ECHO (2017)

transboundary in nature and require greater cross-country collaboration to prepare and respond to crises (Boin et al. 2014a). Therefore, it has been necessary to create integrated institutions and coordinating mechanisms to manage these. We outline key institutions that have developed and explores how they have evolved and how they respond to the challenges of Europe's changing risk environment.
Crises in the future will be increasingly transboundary, transcending geographic and political borders and affecting multiple vital elements of infrastructure, and will not be contained in time (Ansell et al., 2009; Ansell et al., 2010; Boin and Ekengren, 2009; Boin and Lagadec, 2000). Recognising this, the European Security Strategy (ESS) declares: 'the EU's commitment to combat a variety of security threats, including failed states, energy security, terrorism, global warming and disasters. The ESS adopts a comprehensive view, explicitly linking internal and external threats, civilian and military capacities and natural and man-made disasters' (Boin and Ekengren, 2009). This points to the importance of effective cooperation between regional, national and international communities.

The UCPM, established in 2001, seeks to enhance and strengthen cooperation and coordination between Member States and to jointly respond to major emergencies — including pooling capabilities (Morsut, 2014). The mechanism has evolved from preparedness for response, and response, to include preparedness and prevention, and in supporting international relief efforts, for example to the 2004 Indian Ocean tsunami and the 2010 Haiti earthquake (Morsut, 2014).

Evidence points to the value of information sharing in disaster response, with studies showing that failure to do so '… during interagency disaster response has a negative influence on collective decision-making and actions' (Bharosa et al., 2010). This has been recognised by European members, including the Dutch Ministry of the Interior and Kingdom Relations (Bharosa et al., 2010). The UCPM promotes a coordinated response to disasters across Europe (see Box 5.4) supporting countries when capacity if surpassed. However, empirical evidence is sparse on the challenges and obstacles to effective coordination and information sharing, limiting understanding of the means to address barriers between community, agency and individual levels (Bharosa et al. 2010).

Overall, Europe's approach to preparedness and response can be categorised as a 'networked approach' reflecting the complexity of recent disaster events (Boin et al., 2014a). Europe's recent experience with disasters that cross traditional geographic and policy boundaries — referred to as 'transboundary crises' — include the bovine spongiform encephalopathy crisis in 1996; the Erika and Prestige tanker disasters in 1999 and 2002, respectively, with devastating environmental, social and economic impacts; flooding in central and eastern Europe in 2002; and fires in southern Europe in 2003 (Boin et al., 2014a). Throughout 1990 and 2000 the European Union developed its transboundary coordination and cooperation in response to different crises, harnessing European capacity and leading to the establishment of several agencies: the European Food Safety Authority, the European Maritime Safety Agency and three European financial supervisory authorities (Boin et al., 2014a). The development of tools, approaches and institutions has therefore been largely reactive, whereby 'The EU developed all of this capacity in a punctuated and fragmentary manner: with each crisis, Member States invested additional authority in the Union's budding crisis management apparatus. There is, in other words, no institutional blueprint' (Boin et al., 2014a). It can therefore be characterised as a 'network' or governance approach (Boin et al., 2014a).

This networked approach is supported by a number of tools, including the ERCC in Brussels (Box 5.4) and a Common Emergency Communication and Information System, which facilitates communication between the ERCC and national authorities. These centres seek to align with the European Union's core values — respect for human dignity, liberty, democracy, equality, the rule of law and human rights.

Progress over the past 20 years has seen research initiatives move from a focus on cross-border cooperation between Member States to methodological development. The latter includes hazards such as earthquakes, floods and landslides, as well as more effective management plans linked to EWSs employing those new technologies (Papatheodorou et al., 2014). Papatheodorou et al. (2014) note that '… harmonisation of methodologies used to assess ELF Hazards (earthquake, landslide, flooding), easy or even free access to reliable and accurate harmonised data and reliable and accurate hazard maps on a local scale are needed in order to effectively design preventive measures, to plan an effective management strategy and finally to raise public awareness'.

Initiatives such as EFAS support improved preparedness to flooding in transnational European river basins (Thielen et al. 2009). Starting with a 2003 prototype, local water authorities were provided with 3-10 days advance notice of medium-range and probabilistic flood forecast information. Initiatives such as these involve collaboration with national hydrological and meteorological services linking research, action and continual development of a model supported by information exchange and linking meteorologists with national water authorities. When initiated, EFAS was one of the few flood warning systems in existence to utilise ensemble prediction systems to increase predictability of floods and enhance preparedness capacity (Thielen et al., 2009). The importance of cross-border cooperation is especially important for flood hazards, providing means to strengthen knowledge, information and selection of cost-effective mitigation strategies. The lack of a legal framework for cooperation, of capacity and resources and of differing institutional structures and public awareness present challenges to be addressed (Papatheodorou et al., 2014). Effective cross-border action is limited without comparable pan-European methodological approaches to hazard assessment and risk mapping (Papatheodorou et al., 2014).

BOX 5.5

European community urgent radiological information exchange (Ecurie)

In the wake of the Chernobyl accident, Council Decision 87/600/Euratom was adopted. This decision essentially obliges a Member State to notify the European Commission without delay in the event of enacting measures to protect its population from the effects of an event with radiological consequences. This legislation was the legal basis for what became known as the 'European community urgent radiological information exchange', or Ecurie, and was a major step forward in the field of radiological emergency preparedness in Europe.

The information to be shared not only covers the basic characteristics of the event itself but also the foreseeable development of the emergency and its potential effects, the results of radiological monitoring in the affected country and the measures taken to provide information to the general public. On receipt of such a notification, the European Commission promptly forwards the information to all Ecurie contact points. The intention is for the system to provide a continuous flow of information during the emergency.

In the years since, the system has matured both in terms of stakeholder network and operational status. A new information exchange software application, 'Web-Ecurie', was developed and first made operational in 2012, replacing its predecessor, which was based on point-to-point secure email communication. Users only require internet access in order to enter the application, which may be used on a variety of platforms. Submitted information is organised in a modern status board arrangement. 'Event' or 'National' status boards allow for either a broad or a country-specific view, with particular focus on the display of national protective measures.

Much attention has been and continues to be given to harmonising the underlying procedures and technology with that of the International Atomic Energy Agency, and the transfer of valuable experience gained over the decades in Europe to countries and regions outside the European community is actively being pursued.

Source: De Cort et al. (2015)

5.2.1.3 Developing effective early warning systems

EWSs form an important part of DRM and are essential features of UCPM (Alfieri et al., 2012). Greater recognition of the role of EWSs have contributed to the move from an ex post response towards a culture of risk prevention and preparedness (Alfieri et al., 2012). The shift to greater stakeholder participation in preparedness and response (described earlier in this chapter) can be seen in more accessible and open information in EWSs including the ability of systems to be accessed remotely and stakeholders to input data that improves the quality of early warnings (Alfieri et al., 2012).

EWSs provide timely warnings to minimise loss of life and to reduce economic and social impact on vulnerable populations (Garcia and Fearnley, 2012). In 2006, the UNISDR platform for the promotion of early warning published the Global survey of early warning systems, identifying existing capacities and gaps in EWSs in over 23 countries with 20 international agencies (United Nations, 2006). The report advocates that an EWS should be 'people centred' (i.e. community based) and should include many systematic approaches and diverse activities spanning four key elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability (Basher, 2006). The operation of an EWS presents numerous challenges due to variations in scale (global, national, regional or local), temporality (rapid onset or slow onset and frequent or infrequent), function (safety, property or environment) and hazard (weather, climate and geohazards).

An EWS needs to fit within the broader mitigation and preparedness actions of the DRM cycle. Researchers and other stakeholders frequently work independently on EWS subsystems in a multitude of non-coordinated strategies with no structure or linking, compromising the effectiveness of the EWS. An effective EWS can only be achieved once stakeholders recognise their relative contribution and work together to link efforts in order to achieve effective DRM.

With the increasing impact of global warming on extreme natural hazards, EWSs are increasingly required to cater for multiple hazards (Basher, 2006) or even cascading hazards (Pescaroli and Alexander, 2015). This is reflected in the SFDRR — and its European signatories — which aims to 'substantially increase the availability of and access to multihazard EWSs and disaster risk information and assessments to the people by 2030' (UNISDR, 2015). This requires a greater examination of the role of EWSs as a whole within preparedness strategies.

5.2.2 Ethical, legal and social principles in preparedness and response

We review some of the core ethical, legal and social (ELSI) considerations in emergency preparedness and response. Recent efforts have begun to draw interdisciplinary research together and engage closely with practice (Campbell 2012; Boin and Ekengren 2009) to discuss ELSI. Debates about responsible research and innovation (Nowotny et al., 2001; Von Schomberg, 2013; Stilgoe, 2015) have brought a reflexive dimension to research and practice in DRM.

DRM is embedded in complex ethical, legal, social and political contexts, and disasters should not justify exceptions in moral standards. Shared values and principles are needed for emergency response that transcend national boundaries and strengthen social cohesion and trust before a disaster can increase the effectiveness of response.

Debates about responsible research and innovation (Nowotny et al., 2001; Von Schomberg, 2013; Stilgoe, 2015) have brought a reflexive dimension to research and practice in DRM.

5.2.2.1 Legal frameworks

National legal frameworks for disaster preparedness and response in Europe are based on European Commission directives or international initiatives. As in the case of the Flood Directive (Alfieri et al., 2012), these policy developments often respond to global change or large-scale disasters. The Flood Directive, for example, shows how major European floods have resulted in a move towards uniform protection for all European Union citizens and call on Member States to review their flood risk management approaches (Alfieri et al., 2012). Directives urging Member States to strengthen preparedness measures are often closely linked to mitigation strategies and environmental protection actions, including the Strategic Environmental Assessment (Papatheodorou et al., 2014). This is largely the case for earthquakes, floods and landslides (Papatheodorou et al., 2014).

With a shift towards a risk management approach to dealing with disasters, the legal frameworks under which preparedness and response are situated have broadened. The attraction of 'risk-based regulation' has been discussed by scholars reflecting on the increased adoption of 'risk' by policymakers — including the European Commission, which regards risk as a 'crucial' component of public policy, and the Organisation for Economic Cooperation and Development's recommendation of risk-based approaches (Krieger, 2013). Disaster preparedness and response has evolved in this context of risk-based governance, regarded as a means to operate more efficiently with finite resources in a context of austerity and accountability in the context of a narrative of 'good governance' (Krieger, 2013).

Increased incidents of flooding and economic damage since the 1990s — and, in particular, USD 11 billion (EUR 10.1 billion) of damage as a result of the Elbe/Danube flood in 2002 and USD 4 billion (EUR 3.7 billion) in the United Kingdom in 2007 — have reinforced this paradigm shift and there has been a clear move from flood defence to flood risk management across Europe (Krieger, 2013). This can be seen in the United Kingdom's 'Making space for water' (DEFRA, 2004) and Germany's 'Room for rivers' approaches (Krieger, 2013).

As with many EU Member States, the United Kingdom emergency management approach is 'all hazards' and incorporates mitigation, preparedness, response and recovery (O'Brien, 2008). Emergency management is characterised as 'legally based, professionally staffed, well funded and organised' (O'Brien, 2008). Reforms to United Kingdom emergency management have replaced discretion with a duty to prepare plans, standardising procedures for risk assessment and supporting a more integrated approach. Emergency management in the United Kingdom has, however, been criticised for focusing largely on institutional resilience and organisational preparedness where a greater emphasis on societal resilience and public preparedness is regarded as necessary (O'Brien, 2008). Greater emphasis on a preparedness and emergency planning that moves beyond the focus on the continuity of emergency services and commercial activities could entail greater inclusion of the public (O'Brien, 2008).

5.2.2.2 Ethics and moral standards for emergencies

Disasters are often still seen as justifying exceptional decisions. Sorrell (2002), for example, argues that in emergencies, societies may be 'sucked into a moral black hole'; meaning a breakdown of moral and social order that justifies the use of extraordinary powers. These positions are, however, challenged by a number of analysts. At the root of these debates are questions about whether moral standards should ever be disregarded in emergency situations.

As part of its code of ethics, the International Committee of the Red Cross (ICRC) provides detailed guidance on how to engage local populations in conflict areas in the production, protection and sharing of sensitive information (ICRC, 2013). These approaches make the case that preparation can protect societies from exceptions that go against ordinary morals, integrity and dignity, from unintended consequences or from entrusting decisions solely on experts or governments without public engagement. This resonates strongly with calls for responsible research and innovation, process-oriented, 'post-ethical, legal and social issues' approaches (Balmer et al., 2016) that develop forms of disclosure and ethics (Introna, 2007), collective experimentation (Petersen et al., 2016) and collaborative design (Liegl et al., 2016) to address ELSI as they emerge in DRM.

Community involvement in DRM is generally agreed to be essential and is widely promoted internationally. While states have an ethical and often legal responsibility for preparedness and response, effective action requires society as a whole to engage and the government to partner with civil society and private sector organisations. The shift towards civilian disaster preparedness and response recognises that 'disasters can only be mitigated successfully if ordinary people are empowered to take responsibility for their own safety. Disasters, therefore, are as much about democracy as they are about security' (Alexander, 2002). Guiding principles for state interaction with society in preparedness and response have been highlighted by international agencies, including 'empowering and inclusive participation', 'accessible and non-discriminatory support' and the 'special attention [needed for] those disproportionately affected by disasters' (UNISDR, 2015). Indeed, emergency preparedness is considered by some as a means to ensure and safeguard democratic rights, not to circumvent them. Thus, civil protection often explicitly includes principles of equity (Wisner et al., 2004; Alexander, 2002) and the Council of Europe's European and Mediterranean Major Hazards Agreement has published extensive guidance on the application of ethical principles to all aspects of DRM (Prieur, 2012).

Accountability, which is a key principle behind community participation and involvement, is encouraged by international, regional and national codes, charters and standards (Twigg, 1999). For international humanitarian response, the International Federation of the Red Cross/International Committee of the Red Cross has a code of conduct, a voluntary code of principles for humanitarian actors (IFRC/ICRC, 1994), while the Sphere Project has developed a set of minimum standards in core areas of humanitarian assistance (Sphere Project 2011) and the Inter-Agency Standing Committee has prepared operational guidelines on human rights and natural disasters (IASC, 2006). In Europe, the 1998 Aarhus Convention established public rights to information on the environment and associated human safety as well as to participate in relevant decision-making (UNECE, 1998). Such instruments may be linked to or supported by broader principles and agreements on human economic and social rights and to institutions that monitor and support them. The idea of a 'right to safety' is supported implicitly in some international covenants and charters, although it is rarely recognised in national legislation (Twigg, 2003).

Public debates regarding ethical aspects of preparedness and response are often triggered by disasters, such as the L'Aquila earthquake trial (Alexander 2014, Newberry 2010), but are also ongoing, wider discussions about social justice and vulnerability, both internationally (Wisner et al., 2004; Morrow, 2008) and within the European Union (Brisley et al., 2012; Fielding, 2007; Lindley et al., 2011).

5.2.2.3 Social capital and social cohesion

Research points to the very important role of social capital as a primary base for community disaster response and is vital in reducing the impact of disasters and facilitating recovery (Dynes, 2002; Ko and Cadigan, 2010; Murphy, 2007; Aldrich, 2012). In crises, social networks provide mutual assistance and access to support and resources, thereby reducing disaster impacts and facilitating recovery. This has been demonstrated by research in a number of countries, notably Japan and the United States, but there is a need for further research in Europe (Comfort, 1996; Dynes, 2005; Murphy, 2007; Airess et al. 2008; Aldrich, 2012; Aldrich and Meyer, 2015; Nakagawa and Shaw, 2004; Shaw and Goda, 2004; Wallace and Wallace, 2008; Minamoto, 2010; Mimaki and Shaw, 2007).

Disasters often encourage or reinforce social capital formation (Putnam, 2000; Gordon, 2004; Shaw and Goda, 2004; Bankoff, 2007; Yamamura, 2010). Studies mostly show a strong association between , levels of social capital and post-disaster mental health outcomes, particularly a reduction in post-traumatic stress (Wind et al,. 2011; Wind and Komproe, 2012; Ritchie and Gill, 2007; Adeola and Picou, 2014; Ganapati, 2012a, b). Conversely, an acute lack of social capital — social isolation — can contribute significantly to vulnerability, as documented with regards to the European heatwave of 2003 (Keller, 2015; Klinenberg, 2002; Ogg, 2005; Romero-Lankao et al., 2012).

5.2.3 Professionalization of citizen engagement in preparedness and response

At a national and regional scale, over

the past decade the professionalism and coordination of preparedness for response by civil protection mechanisms, including across states, has advanced significantly. Some of these tendencies and an analysis of the changing roles of different preparedness and response actors are described below.

The professionalism and coordination of preparedness and response by civil protection agencies has advanced significantly in recent years alongside a desire to give citizens increasing responsibility for individual preparedness and response. New social groups can emerge during a disaster to help manage emergency response measures — their role could be better harnessed if appropriately planned for informal responses.

5.2.3.1 Citizen engagement and volunteerism

Locally organised, trained and equipped responders are considered a societal asset and a means to enlist significant social capital and capability in preparedness and response. Thus, in some contexts, citizens are encouraged to play a more active role in preparedness and response. The 2014 Dutch National Council for all safety regions — the decentralised bodies responsible for disaster management — recognised the value of untrained citizens and their role in preparedness (Veiligheidsberaad, 2014).

Encouraging preparedness for rare disasters, however, remains a policy challenge. Citizens primarily prepare for incidents perceived to be a significant threat and/or the most recent disaster they encountered (Major, 1999; Tierney, 1989). Government programmes aiming to boost resilience therefore need to focus on dominant and regularly experienced risk. For example, in areas that regularly experience small earthquakes, citizens can be more easily persuaded to prepare for the risk of a more severe earthquake, but less for other risks. This raises questions about, for example, preparedness measures by citizens for flood risk in the Netherlands where the perception of flooding from the sea is low, having not occurred since 1953. In spite of government flood risk preparedness programmes, further efforts are needed to engage citizens (Engel et al., 2012).

5.2.3.2 Emergent groups

Emergencies stimulate informal responses by spontaneous, self-organising and voluntary groups and individuals from within and outside disaster-affected communities. These groups may carry out a wide variety of activities including search and rescue, first aid, damage assessment, debris removal, handling of bodies, relief supplies distribution, food provision, translation, counselling and presenting survivors' grievances (Quarantelli, 1994; Stallings and Quarantelli, 1985). This 'emergent' and 'convergent' behaviour in disasters has been documented over several decades across the world, in different cultures and under a variety of governance structures (Comfort 1996; Drabek and McEntire 2003; Dynes et al. 1990; Linnell 2014; Neal et al. 2011; Quarantelli 1993; Rodriguez et al. 2006; Whittaker et al. 2015). In some cases large sections of populations are involved (Quarantelli, 1993). Extensive flooding in Kingston upon Hull in the United Kingdom in 2007 stimulated a range of spontaneous actions by local residents, including assisting with evacuation, giving care and support to vulnerable neighbours, protecting houses against floodwater and giving medical assistance (Neal et al. 2011).

Large numbers of spontaneous volunteers can present significant coordination, integration, communication and logistical and health and safety challenges to emergency managers, especially in rigid 'command and control' disaster management structures that do not plan for community engagement.

Improvisation and creativity are required to build networks and relationships between organisations and incorporate volunteers within organised efforts (Alvinius et al., 2010; Cone et al., 2003; Drabek and McEntire, 2003; Kendra and Wachtendorf, 2006; McEntire, 2002; Majchrzak et al., 2007; Uhr et al., 2008). Nevertheless, emergency volunteerism offers longer-term opportunities for more structured citizen response through training and creation of community preparedness and response teams as well as through formal voluntary organisations (Alexander, 2010; Barsky et al., 2007; Helsloot and Ruitenberg, 2004; Pardess, 2005), although efforts are necessary to maintain volunteer motivation (Brand et al. 2008). Red Cross national societies are a major provider of organised volunteer support in disasters, with approximately 17 million active volunteers in 190 national societies worldwide (IFRC, 2016). Technisches Hilfswerk, a German government agency, has over 80 000 volunteers (99 % of its membership) who assist in disaster response in their own countries as well as in others (THW, 2016).

Recognition of the contribution that social groups can make in emergen-

BOX 5.6

Digital humanitarianism and citizen mobilisation

There has been a 'digital tsunami' (European Commission, Future Group, 2007), with individuals, objects and environments generating vast amounts of data through self-disclosure and sensors, while advances in data processing make this data amenable to analysis for commercial, governance and security purposes — and DRM (Thrift, 2011). Together, these advances can enable improvements in preparedness and disaster response because they provide communities with more broad-based and detailed monitoring and timely feedback on their situation and support predictive modelling and more precise targeting of assistance.

'Digital humanitarianism' (Starbird and Palen, 2011; Munro, 2013; Burns, 2015) can be extremely useful if addressed within a framework for resilience that places an emphasis on data ownership, community-based analytical authority and community-based data skills (Crawford et al., 2013). Social media is one aspect of the role of technology in citizen mobilisation and awareness raising.

Social media can also service self-organised mobilisation and coordination of local resources, knowledge and efforts. During the floods in Germany in 2013, for example, 29 % of Twitter messages focused on coordinating help and resources locally (Zipf, 2013). Reports from sandbag-filling stations appeared alongside calls for help and a crowdsourced map of the current need for volunteers in different places (Mildner ,2013). Lüge (2013) suggests that these examples index a shift in the use of social media for emergency management. The informational service function for official response is increasingly seriously complemented by a practical service function for self-organised community help and resources, especially for members of the public. Recent studies find that in Europe generally, social media are growing and supporting the emergence of new forms of 'social resilience' (Flizikowski et al., 2014, Reuter and Spielhofer, 2016).

The use of social media in crises can give rise to rumours (Mendoza et al., 2010), vigilantism and 'do-it-yourself' justice (Rizza et al., 2014, Tapia and LaLone, 2014). However, attempts at structuring digital volunteer work and crisis mapping through the UN co-founded Digital Humanitarian Network (Meier, 2015) and Virtual Operations Support Teams or 'VOST' (St. Denis et al., 2012) have begun to create bridges between crisis mappers and formal emergency agencies (Kaminska et al., 2015). They establish networks of trust: mechanisms that combine standardisation, training, and agreed channels of communication that enhance risk governance. These include engagements around air pollution (Mosley, 2009) and radiation risks from Chernobyl where 'descriptive standards', 'alignment', 'unblackboxing' and 'mobile measuring' proved central to prevent risks from becoming 'twice invisible' (Kuchinskaya, 2012).

cy response has stimulated positive changes in state-civil society relationships for disaster planning. Yet governments sometimes resist in order to maintain control (Jalali, 2002), and extensive government activity and spending can crowd out voluntary activity, especially where autonomous civil society is not well developed (Deng, 2009; Teets, 2009).

5.2.3.3 The role of social media in citizen engagement

Knowledge of crisis communication in Europe is growing rapidly (Palttala et al., 2012). A complex field in itself, crisis communication links to societal expectations over the role of public authorities to effectively communicate risk and educate citizens on effective preparedness and response. Coordination has become increasingly important, as responsibility for managing crisis moves from solely the government and emergency services to include the role of media, social media and other actors (Palttala et al., 2012). Despite differences between countries — including different levels of financial resource for public crisis communication — the growing body of evidence, a plethora of guidelines and best practice, suggests there remain gaps in ensuring communication is integrated into disaster management practice and an integral part of decision-making (Palttala et al., 2012). Gaps remain in relation to cooperation across actors, i.e. the media, with citizens and across the response network (Palttala et al., 2012).

New forms of self-help, partnership and cosmopolitan 'digital humanitarianism' become possible with technology. Watson and Finn (2014), for example, examine information flows between corporations and their customers during the Eyjafjallajökull eruption, the most severe global flight disruption since 9/11. This empowered improvised self-help, including self-organised information services, and support for actively coordinating alternative travel. It widened people's networks through 'virtual social convergence', and Watson and Finn (2014) conclude that 'such activities are able to enhance citizen resilience by mobilising social capital'.

5.2.4 Conclusions and key messages

Partnership

Cooperation between regional, national and international communities is needed for preparedness and response planning given the complex and transboundary nature of modern day disasters. ELSI are dimensions of DRM that need to be addressed together with practical efforts to prepare and respond. Effective preparedness can protect societies from exceptions that go against ordinary morals, integrity and dignity, from unintended consequences and from entrusting decisions solely on experts, or governments without public engagement.

Knowledge

A move away from command-and-control approaches to managing disasters has opened up more opportunities for citizens to participate in preparedness and response. Strong bonds and trust within and between communities facilitates a more effective response in emergencies and can be harnessed by authorities. Social media can also be used to enhance self-organised mobilisation and coordination of local resources, knowledge, and efforts for disaster preparedness and response.

Innovation

Research and innovation in process-oriented approaches to ELSI will improve collective experimentation and collaborative design, to address issues as they emerge in the dynamic contexts of disaster preparedness and response.

5.3 Recovery and avoiding risk creation

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5.3.1 Introduction

Most disasters are difficult to predict in the short term, but research to quantify the impact and understand recovery processes can help reduce the uncertainties associated with these events. Recovery is, however, the least understood aspect of DRM (Smith and Wenger, 2006). It is considered a complex, non-linear process with physical, social, economic and institutional dimensions (Johnson and Hayashi, 2012; Alexander, 2016). The recovery period is also an opportunity to facilitate economic, social and physical development long after the disaster (Berke et al., 1993); and the promotion of social and intergenerational equity is a key principle for sustainable recovery.

In this subchapter we examine scientific knowledge of recovery processes and the policies that have been implemented to enhance recovery, focussing primarily on Europe. Europe has experienced a range of disasters in recent years, though perhaps with less frequency and intensity than other parts of the world.

It is important to be prepared to live with the possibility that disasters may occur in one's lifetime or in that of the next generation. Anticipating the multiple dimensions of recovery is key to effective risk management.

The aim is not to provide an extensive coverage of all disasters or hazard types but rather cases that have been illustrative of the recovery process and that have led to scientific innovations and advances in theory. Not all recovery processes are covered here, but authors have attempted to cover a range of physical reconstruction and economic, social and psychological aspects, as well as knowledge about the planning and coordination of measures aimed at assisting recovery.

Europe is the focus of analysis, but whenever experience from other locations helps to understand recovery processes and policies in Europe, these are mentioned. Within Europe there are differences between north and south, not only in the types of hazards that are prevalent, but also in the cultural processes shaping recovery. These are mentioned here but not explored in detail due to space restrictions.

5.3.2 Planning for recovery

The recovery process is multidimensional and progresses at different rates for different people, businesses, institutions and places affected by a disaster (Wein et al., 2011). Institutional fragmentation and short-term planning can hinder recovery and often result in new risks being created. Thus, cross-scale and longer-term strategies are needed in recovery, integrating different stakeholder perspectives and knowledge and coordination across policy domains. Innovations in our understanding of recovery planning are discussed in this section and provide a starting point for a deeper exploration of recovery processes later in the subchapter.

5.3.2.1 Recovery plans

The core purpose of disaster recovery planning is to offer a vision of the future after a disaster, provide a direction-setting framework (strong fact base, goals and policies) to achieve the vision; ensure that even short-term actions build longer-term resilience and that community needs are linked to broader regional, state and national disaster response and reconstruction policies (Berke and Campanella, 2006). Successful plans maintain both a combination of as well as distinct short-term recovery and long-term planning goals (Ingram et al., 2006).

Recovering from damage, loss and social disruption involves different types of activities. Categorising the impact can provide focus for both planning and research activities. Common recovery sectors are: reconstruction of buildings, restoration of livelihoods, system repairs, human and social rehabilitation, amongst others, to restore society back to being a well-functioning community, and preferably a better functioning community. Lindell and Prater (2003) define disaster impact sectors as physical (both built and human) and social (psychosocial, sociodemographic, socioeconomic and political); while Davis (2006) divides the process into five sectors, psychosocial, economic, physical, environmental and administrative/institutional sectors. Overall, identifying and classifying areas of recovery is best done on the basis a Post-Disaster Needs Assessment (PDNA). PDNA is a common assessment approach to support governments to assess damage and recovery needs. It is an inclusive process that builds on the capacity and expertise of national and international actors (GFDRR, 2013). PDNA provides damage and loss estimates and quantifies needs. A recovery framework is then needed to build on the damage and loss assessment for detailed sequencing, prioritisation, financing and implementation of recovery efforts.

Pre-disaster planning, participatory planning, capacity building, scheduling and process coordination can all help improve recovery and build more resilient communities.

Recovery goals commonly include the timely restoration of normal living conditions (Alexander, 2004; Lu and Xu, 2014); however, there is a trade-off between speed and deliberation (Olshansky, 2006; Lu and Xu, 2014). Pressure to urgently address complex, difficult decisions can result in reactive policies that may increase long-term vulnerability of affected populations (Ingram et al., 2006). Time compression has thus been identified as an important overarching characteristic of the recovery process (Olshansky et al., 2012).

5.3.2.2 Integrating mitigation in recovery plans

Disaster recovery provides opportunities for reducing risk through mitigation measures (Ingram et al. 2006). Mitigation measures should be integrated into pre-disaster recovery planning (NGA, 1979; Alexander, 2004; Lu and Xu, 2014) and can include proposals to reform building codes and land-use plans as one of the steps needed to meet recovery objectives (along with reconstruction, restoring systems, rehabilitation of people and re-establishment of livelihoods) (Thorvaldsdóttir and Sigbjornsson, 2014). Methodologies developed for evaluating benefits and costs of disaster mitigation measures (e.g. Chang, 2003) can also be used to guide the recovery process, although CBA needs to be used carefully (see Chapter 5.1.5).

5.3.2.3 Promoting participation

Recovery is also considered an interactive problem requiring coordination between numerous agencies and stakeholders (Berke and Campanella, 2006; Lu and Xu, 2014). Research on actors includes: the role of local officials (Rubin and Barbee, 1985), affected people (Ingram et al., 2006), citizen participation (Kweit and Kweit, 2004), the private sector (De Tura et al., 2004), community participation in general (Johnston et al., 2012) and auditors of the planning and implementation of recovery (Labadie, 2008). The role of partnerships (Mitchell, 2006) and management types (normal line ministries, special task force of government and new organisation) (Davis, 2006) are also addressed in the literature.

5.3.3 Reconstruction, building and urban design in post-disaster contexts

5.3.3.1 Principles for reconstruction

In post-disaster reconstruction, location and exposure to risk are important considerations, as are the type of construction materials, the constraints on materials (due to environmental conditions), timing of execution and access. Understanding the appropriateness of different materials that would be needed for reconstruction prior to a disaster can speed up reconstruction decisions, although the disaster itself will create new challenges. In the 1755 Lisbon earthquake (Oliveira, 2012), for example, scientific knowledge was lacking and guidelines for reconstruction (new urban design, introduction of seismic and fire-resistant techniques, new sanitary system, etc.) were drawn up quickly alongside a large number of decrees dealing with feeding, healthcare, defence, property jurisdiction, commerce activities and taxes. In comparison, discussion on the types of new defences needed for future tsunamis in the zones affected by the Tohoku tsunami have occurred over several years (Ieda, 2012), culminating in the decision to build big barriers made of concrete or soft dunes to dampen the energy of waters (Figure 5.3).

Disasters affect communities for varying periods of time and reconstruction is often required. Rebuilding poses various challenges, from defining suitable locations to merging tradition with modern construction techniques.

Reconstruction time varies tremendously depending on the level of resilience and the degree of impact of the event. There are cases where reconstruction has been greatly influenced by low pre-existing levels of development and will take a very long time, as is the case of the earthquake in Haiti in 2010. In these cases, the urban systems themselves need to be developed at the same time as reconstruction is happening. In other cases, the value and ownership of property has to be correctly identified and agreed before reconstruction or rehabilitation can begin.

For the historical centre of L'Aquila a roadmap for housing reconstruction was developed and building has been carefully monitored (Murao et al., 2007; Ishikawa, 2012; Chern, 2012). Considerable attention has been paid to discussing options with the affected population to ensure reconstruction decisions are acceptable to them (see Box 5.7).

5.3.3.2 Local construction practices

The process of rebuilding residential property, industrial stock, critical infrastructures and historical buildings is shaped by existing arrangements for urban planning as well as educational, technical and financial resources available. Pre-disaster construction practices, including the mix of 'engineered structures' versus 'low-cost structures' and how building is guided by regulations and land-use/urban plans, all affect the type of reconstruction activity that is appropriate and necessary. The political system also affects the success of a reconstruction process (Lucas et al., 1992; Oliveira et al., 2008).

Table 5.3 provides an intentional oversimplification of reconstruction options and the norms guiding these in countries of 'higher income' and of 'lower income'. Understanding the most common reconstruction techniques used and other considerations influencing reconstruction patterns is really important. For engineered structures, codes of practice and technological tools can help guide reconstruction. In particular, EN-1998-3 (2005) is a code of practice to guide reconstruction and rehabilitation of structures, but needs to be adapted to a country in accordance with material properties, techniques of reconstruction, etc.

The knowledge contained in codes needs to be communicated to the technical community and to practical contractors through manuals as well as training courses, and even using the media to reach a broader population. Codes that are efficient but not too complex are more likely to reduce non-compliance. For 'low-cost structures', on the other hand, building techniques that are compatible with traditional practices are more effective, adjusting the codes to local materials and local traditions.

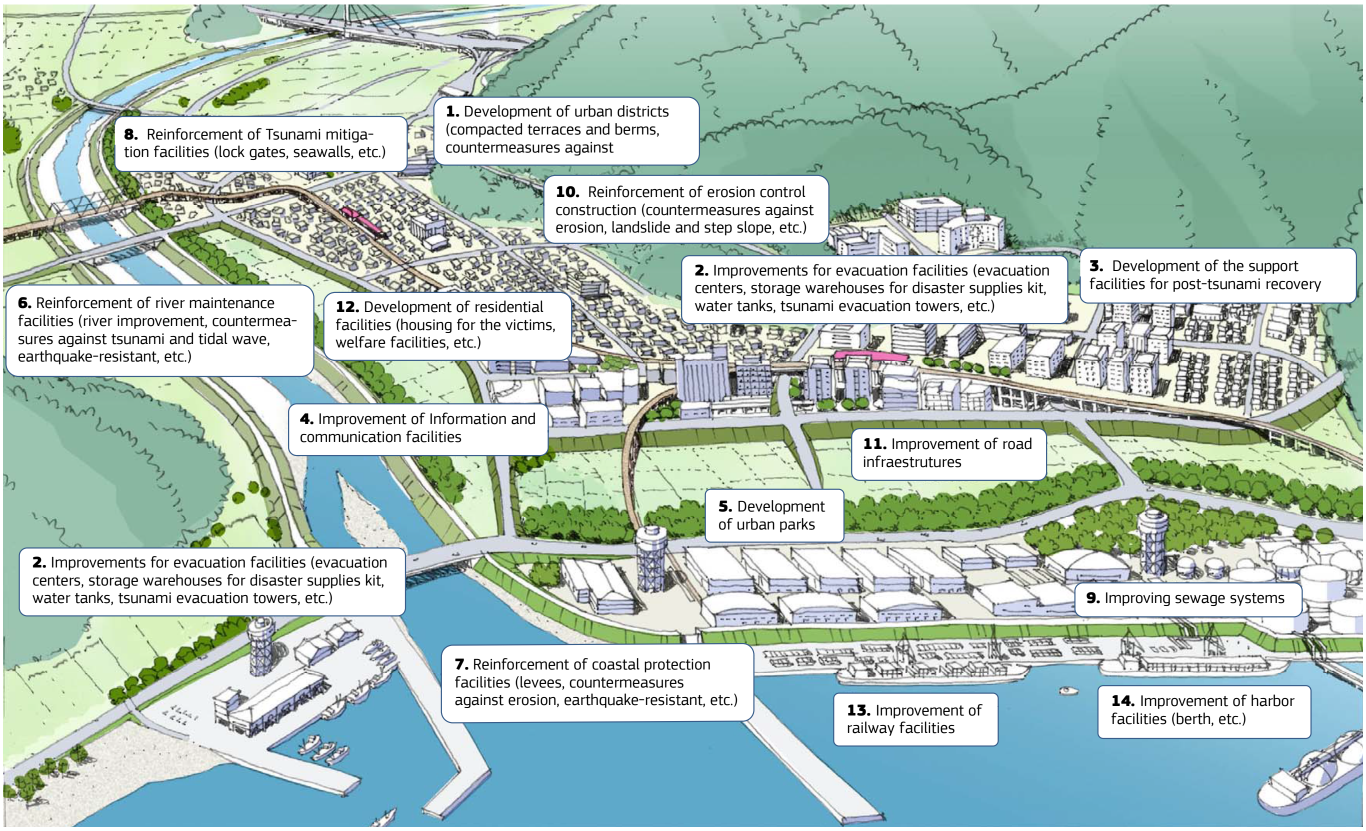
5.3.3.3 Avoiding future risk

Housing and other structures can be relocated to areas where exposure to hazards and other sources of risk is a lesser problem. Techniques can be used to weigh the various components of risk. For instance, 'Sirius' (Mota de Sá et al., 2013) is an indicator referring to geographic zones which are more prone to urban impact in case of an event. It deals with two variables, one concerning the vulnerability of the existing housing and the other reflecting the human concentration. It is organised into several plateaus which define the level of impact for that event. The opinions of those affected on whether to rebuild in the same place or move to another environment is also of great importance.

Reconstruction can be used to correct urban development problems, such as high population concentrations, and to widen roads for more

FIGURE 5.3

Sketch of possible solutions for Tohoku earthquake.
Source: MLIT (2013)



effective drainage. The case of Italy, with the several earthquakes in the last 25 years, is critical (Dolce and Bucci, 2015), and the project C.A.S.E. (Costruttori ForCase, 2009) is particularly relevant for avoiding future risk, where new buildings have been constructed in a short period of time with base isolation.

Similarly, the Guidelines for seismic microzonation (SM Working Group, 2015) and the European Floods Directive (European Parliament and Council, 2007) are good examples of how to minimise risk through reconstruction after major disasters (European Parliament and Council, 2007; IPCC, 2014; Thaler and Hartmann, 2016). Reconstruction after the floods in the Netherlands in 1953 is, however, perhaps the most striking example of taking measures to control flood risk in the future (See Box 5.8).

Another example of significant mitigation measures being taken to limit risk in the future in the wake of a high-impact disaster can be found in Madeira (see Box 5.9).

BOX 5.7

Temporary housing construction in recent Italian earthquakes

On 24 August 2016, a M6.0 earthquake started a seismic sequence in central Italy, which included a M6.5 event on 30 October 2016. There were at least 299 fatalities, essentially caused by the collapse of buildings during the first main shock.

So, how should long-term temporary housing be managed after an initial period in tent and caravan campsites or hotels and before reconstruction takes place? A variety of responses can be seen after the three strongest earthquakes occurred in Italy in the past 30 years: Umbria-Marche in 1997, Abruzzo in 2009 and Emilia in 2012. Due to the long lapse of time typically required in Italy to complete the repair and reconstruction process — especially for the historical centres — housing arrangements are needed for homeless families for several years. Different solutions have been adopted (Dolce and Di Bucci, 2015). In Umbria-Marche and Emilia, the temporary solution consisted of public contributions to autonomous construction or, alternatively, pre-fabricated homes. In Abruzzo, four different alternative solutions were conceived for about approximately 45 000 people.

The first two consisted in the requisition of unused apartments and in a monetary contribution for autonomous lodging arrangement. Moreover, two ad hoc projects were set up and realised. The project C.A.S.E. consists of seismically isolated three-story buildings that can host around 15 000 people in 4 449 apartments. It was completed 10 months after the event. The limited land needed made them suitable for the city of L'Aquila. The project M.A.P. consisted principally of single-family timber houses in small settlements near the original villages. In total, 3 535 houses were erected in 141 areas, for approximately 8 500 people. For the Amatrice sequence, the choice was to use monetary contributions or 'Emergency housing solutions' similar to the M.A.P.s housing.

All of the described choices have a sound rational basis and could be adopted under different conditions. For the earthquake disaster recovery there is no 'one size fits all' model. Territories are different, available scientific and technologic support evolves and the expectations of the affected population change over time. A mature civil protection system looks for tailored solutions, building on previous experience while exploring new alternatives.

5.3.4 Economic recovery processes from households to the macro economy

Economic recovery refers to the process by which an economic unit (household to country) returns to conditions of stability following a disaster (Chang and Rose, 2012). Recovery does not require returning to a pre-disaster state; in fact, economic systems may never return to pre-disaster states, but rather achieve a new equilibrium (DFID, 2011).

In this section we examine knowledge on recovery processes that take place at different scales after a disaster. This literature draws on a wide range of post-disaster experiences in many different countries.

5.3.4.1 Economic recovery processes at the microlevel

The processes that enable households to recover levels of wealth after a shock or a disaster have been extensively studied (see, for instance, Christiaensen et al., 2007; Dercon and Christiaenen, 2011). In the short term after a disaster, incomes drop and the loss in income can lead to a reduction in consumption, with direct impact on individuals within the households, including higher levels of malnutrition (Alderman et al., 2006; Beegle et al., 2006).

The recovery process begins immediately but partially depends on the initial economic situation of the household: diversified sources of income and relatively high income levels are found to be beneficial for recovery across a range of countries and contexts (Adger et al., 2002; Morris et al., 2002). High levels of assets as well as access to credit, government grants and social protection give people a wider range of options and opportunities following a disaster and can speed up recovery (Twigg, 2015).

Measures can be taken to support and accelerate the economic recovery process at various scales, although the economy may not return to the pre-disaster state.

Social networks, safety nets and remittances play a particularly important role. These mechanisms are often ignored by DRM policies (Gaillard and Le Masson, 2007), yet social and physical connections are a major factor in people's vulnerability to disas-

TABLE 5.3

Matrix of construction types
Source: courtesy of authors

Structures, technologies and related norms	Higher-income countries	Lower-income countries
"Engineered"	Home made	Imported
"Low-Cost"	Contracts	Self-construction
Construction legislation	Comply if compulsory	Need supervision
Urban design considerations	Comply if discussed	Low priority

BOX 5.8

Improving flood defence after the Dutch flood disaster of 1953

Its geographical position means the Netherlands is not only threatened by the sea but also by major (international) rivers (Figure 5.4).

On 1 February 1953, there was a major flood causing significant losses due to high water on the North Sea and a severe northwestern storm. A total of 800 km of dikes were severely damaged and 200 000 hectares of land flooded. The Netherlands was not prepared and the condition of the dikes was inadequate. A more structural approach to preventing damage in the future was needed and a Delta Commission was appointed, the Delta Act passed (Bulletin of Acts, 1958) and the Delta Works project initiated to close off all tidal waters between the Western Scheldt and the Rotterdam Nieuwe Waterweg and to strengthen primary dikes along the coast and the Western Scheldt. The central government decided to fund a massive investment in flood defense: the Eastern Scheldt barrier, with its sliding gates, was considered a technical and expensive innovation at the time but was considered a good investment, saving dike-strengthening costs and promoting Dutch hydraulic engineering.

In 2008 the Delta Commission produced new advice on water safety in the context of climate change and sea level rise. Yearly, delta programmes and a fund have been established and new rights-based legislation passed, guaranteeing Dutch citizens a safety standard (likelihood of dying in a flood disaster is no bigger than 1: 100 000 per year) and stimulating further investment in dike projects. The legal water safety standards are unique in the world and (much) higher than in other countries, and knowledge on water safety is also high. Recent research also suggests that water safety is affordable, costing the ministry (from 1954 to the present day) approximately EUR 35 per capita.

FIGURE 5.4

Netherlands' flood hazard map
Source: Bulletin of Acts (1958)

Virtual coastline shore up in the Netherland
Sea level +1m and flooding in rivers

ters and their capacity to recover from them. Families, neighbours and social networks can help people to recover their assets (Twigg, 2015), while remittances from family members not affected by a shock often increase after disasters (Ebeke and Combes, 2013). Families that have access to remittances can recover more quickly (Savage and Harvey, 2007), as remittances act in a similar way to insurance for people who have no access to these financial services.

Transport and communications infrastructure and support, for instance, in helping people to access credit, as well as other key services, are essential for household recovery.

5.3.4.2 Economic recovery at the business and sectoral level

Disasters can cause long-term structural changes in local economies. According to the Federal Emergency Management Agency in the United States, more than 40 % of businesses never reopen after a disaster (natural or man-made). Over the period 2006-2010, the average commercial flood claim amounted to USD 85 000 (FEMA 2016). Small businesses and financially marginal businesses in particular tend to have greater difficulty in recovering from disasters (Webb et al. 2002; Alesch et al. 2001; Alesch et al. 2009). A recent national survey in the United States estimates that 52 % of small business owners consider it would take at least 3 months to recover from a disaster (Nationwide Insurance 2016). Thus, research on business continuity highlights the importance of strengthening capacity for pre-disaster mitigation and preparedness (Webb et al. 2002; Chang 2010). A business continuity strategy is considered a relevant response to natural disasters for businesses. Cerullo and Cerullo (2004) showed that of all the businesses damaged by Hurricane Andrew in 1992, 80 % of those lacking a business continuity plan failed within 2 years of the storm. In 2014, regarding a Forrester's survey (Balaouras, 2015), the most common scenarios of these plans mentioned by private sector decision-makers included natural

BOX 5.9

Debris flow in 2010 in Madeira Island

Madeira is a mountainous island prone to landslides and debris flow risks. On 20 February 2010 a strong storm occurred with intense rainfalls, provoking flash floods and a mixture of water and sediments came down the very narrow valleys of five streams, killing around 50 people and causing EUR 1 billion of damage. The capital, Funchal, is built on the common alluvial fan of three of these small rivers and was severely hit by the debris. The reconstruction process began, but safe space is very scarce and further measures had to be taken to limit debris floods:

- removal of damaged buildings that were in dangerous flood-prone areas in the valleys;
- rehabilitation and reinforcement of defence walls in the vulnerable areas and in the main urban areas;
- several retention structures (slit dams) were built upstream to reduce the volume of sediment;
- the EU inundation directive is being adapted to Madeira (inundation and risk maps) as well as flood risk management guidelines (land-use guidelines) for 27 critical valleys;
- a warning system based on meteo radar and prediction models, as well as rainfall triggers, is being developed;

Despite the strong difficulties to guarantee completely safe areas against floods, due to prediction uncertainties and the potential high energy flows that can be induced and propagated into densely occupied valleys, it is believed that the protection measures will be able to mitigate future debris flood risk in Madeira.

Source: Gouveia-Reis et al. (2016)

disasters/extreme weather (83 % over 118 business continuity decision-makers and influencers that have or will have scenario-based plans in 2014). The sample is based on a self-selected group of respondents (predominantly Disaster Recovery Journal subscribers and Forrester clients).

Contingency plans can ensure, for instance, the continuity of key activities during a crisis, while recovery plans accelerate the recovery process and limit loss in the aftermath of a shock. A recent study in the United States, for example, found that having an emergency plan was significantly associated with reduced levels of physical damage after Hurricane Ike in 2008 on the Gulf Coast (Xiao and Peacock, 2014). If disaster recovery plans (DRP) and business continuity plans (BCP) are recognised as efficient tools to reducing the impact of natural disasters, most small businesses still do not have any disaster plan. This share is decreasing with the size of the firm. Thus, the nationwide insurance survey showed that 75 % of small business owners who settle do not have such a plan, whereas for one third of them it is a low priority (34 %). For companies with fewer than 50 employees, only 18 % have a disaster recovery plan (National Insurance, 2016).

Disaster can also have a major impact on key sectors. For instance, during the Eyjafjallajökull eruption, the European airlines industry was heavily affected. The International Air Transport Association estimated that airlines lost GBP 130 million (EUR 154 million) per day while flight disruptions cost airlines USD 1.7 billion (EUR 1.56 billion) in total (BBC News, 2010). Other transport companies benefited, however, from the airline disturbance (passengers looking for alternative transport means), but specific fragile and perishable product importation such as flowers was reduced during the crisis period.

The overall recovery process is closely linked to the characteristics of the sector and the value chain. Thus, very large firms, such as multinational corporations are more likely to be well diversified, and localised disasters are unlikely to affect the overall organisation (Stevenson et al., 2016). Horwitz (2009), for example, shows that although Wal-Mart temporarily closed 126 stores after Hurricane Katrina due to major damage, there was little long-term effect on income.

The August 2002 flood in Germany, with a total damage of EUR 11.6 billion, became one of the most expensive natural hazard events in the country (Thieken et al., 2016a). In June 2002, Fischerdorf, across the Danube, was inundated after several levees collapsed, leaving the entire town's small industrial and commercial businesses under 3 metres of water with important consequences on small businesses and individuals. Similarly, a recent survey on German businesses affected by flood in 2013 (557 business interviewed) shows that 60 % were affected by staff absences due to problems of reaching the workplace. Around 80 % of businesses mentioned they were affected by turnover loss and 88 % faced interruption of their operations, sometimes lasting up to 8 weeks with long-term consequences on their activities (Thieken et al., 2016b; OECD, 2016). The 'commerce, hotels, restaurants and transportations businesses' seem to have been the most affected by the event, whereas manufacturing and construction firms mainly suffered 'own delivery problems', highlighting the importance of value chain and vertical integration in supporting recovery. Thus, Thieken's analysis suggests linkages between geographical sectors organisation and unbalanced regional impact of 2013's floods. Consequences of natural disasters on a sector can be regional or global (OECD, 2016). For example, the flooding in Thailand in 2011 had global and regional impacts in the automotive and electronics sectors as global companies such as Toyota, Honda, Nissan, Ford, Apple, Sony, Canon and Toshiba faced disruptions to production as a result of their linkages to sites located in the flood zone. According to Schanz and Wang (2015), global industrial production declined by 2.5 % as a result of the floods (OECD, 2016). These examples suggest that both the sector's organisation and the firm's echelon interplay within the value chain, in addition to the firm's characteristics to influence businesses' recovery pattern.

Economic stimuli are also provided by the reconstruction process and can have a significant impact on key sectors: in particular, construction and other sectors involved in reconstruction often benefit from this (Chang, 2010; Chang and Rose, 2012). Similarly, trade can play an important buffering role in recovery (Bierkandt et al., 2014; Meng et al., 2015), compensating for the lack of products after a disaster. The role of market in the recovery process is essential and is often poorly understood or biased by recovery policies.

5.3.4.3 Economic recovery process at the national level

At the national level, pre-disaster trends are accelerated or exacerbated during the recovery period (Alesch et al., 2009; Chang, 2010), with impacts on gross national product (GNP) or gross domestic product (GDP) and key economic sectors (agriculture; health) highly dependent on the initial level of income and financial penetration (as highlighted after Hurricane Katrina). After a disaster, new investments made in infrastructure and human capital can increase productivity and growth (Skoufias et al., 2011) — a phenomenon known as 'creative destruction', but disasters can also have negative impacts on the economy more than 1 year after the shocks, affecting early recovery (Simonet et al., 2016). Nonetheless, the financial capacity of the country is usually lessened by the recovery process (Cochrane, 2004).

Finally, external funds such as humanitarian assistance can influence the recovery process in both ways (Raghuram and Subramanian, 2008). The absorptive capacity of the country and its ability to smooth temporary and volatile external financial inflows will determine its ability to make efficient use of external assistance.

5.3.4.4 Supporting economic recovery

Accessing financial resources after a disaster is critical to rebuilding and maintaining essential functions (Haworth et al., 2016; World Bank, 2012; World Bank, 2016). Financing at all scales is needed (see Chapter 5.4).

The European Union Solidarity Fund (EUSF) is a good example of efficient risk sharing at the regional level. Created in 2002, the EUSF's objective is to assist the EU Member States in recovering from natural disasters. The fund primarily aims to cover non-insurable loss and to support critical infrastructure such as energy and drinking water during the recovery phase. Since 2002, 24 different European countries have received aid for an amount of over EUR 3.784 million for the recovery (see list of beneficiaries by EUSF (2017)). Flood events are the main disasters leading to the EUSF's assistance to date, which supports the recovery of major natural events (damages exceed EUR 3 billion and the total loss is up to 0.6 % of gross national income of the Member State). National or local events can be considered if the two economic conditions are fulfilled. The annual budget of EUSF is EUR 500 million in addition to the unallocated funds of the previous year. Moreover, rules for disbursement and funds used across each year ensure its sustainability. The EUSF can be combined with other national risk transfer measures such as the one implemented in the Czech Republic, where aid for recovery and reconstruction is provided to municipalities and regions if their budget is not sufficient (OECD, 2015). Thus the combination of national and regional risk transfer measures provides a more efficient coverage of loss in case of disasters. If the fund is a good example of regional, fair and effective risk transfer mechanisms (OECD, 2015; Olsson, 2009), the criteria of the fund's categories, thresholds issues and a significant delay in the fund delivery (Olsson, 2009) could prevent its efficiency. The EUSF is to date the only funds available to support recovery after disasters even if other funds (such as rural development funds) can provide financial aid for prevention activities (Olsson, 2009).

Nonetheless, the policies supporting economic recovery should not focus solely on financing. A mix of policy initiatives is needed to build resilience after a disaster (Twigg, 2015): from the design of Early Warning Systems (EWSs) tailored to specific audiences to the development of efficient regulations. For instance, the work of the European Commission (ECHO) on DRR through providing trainings and policy guidelines, as well as economic support is also essential to support efficient recovery (ECHO, 2016). Overall, combinations of financial support with other market support and service provision are needed. Building an efficient and flexible private sector will speed up the recovery. A good knowledge of the vulnerabilities along the value chain will help to anticipate fracture points and key actions to be taken when there is a disaster. Providing vouchers, for example, is known to have a destabilising effect on local prices.

External assistance after a major disaster can overcome local financial resource constraints but can have what is known as 'a Dutch effect'. If a country cannot smooth or absorb the financial support provided, growth patterns can be destabilised. This occurred after the 2004 tsunami in the

Indian Ocean (De Ville de Goyet and Morinière, 2006).

Overall, economic recovery strategies need to not only consider the short-term impacts of disaster, but also avoid indirect and destabilising effects. Strategies need to consider and avoid environmental impacts and find ways to improve sustainability and resilience. Global Facility for Disaster Reduction and Recovery (GFDRR) frameworks guide of the World Bank provides a good summary of how the combination of policy and strategy settings, financial support, institutional frameworks and implementation arrangements can ensure an efficient economic recovery as well as relevance of timely activities (GFDRR, 2013; 2015).

5.3.5 Psychosocial recovery

Recovery originates in social relationships before disasters occur and more marginal groups usually find it harder to recover (Nigg, 1995; Tierney and Oliver-Smith, 2012). Gender, disability, income and ethnicity are strongly associated with differential recovery trajectories (Cutter et al., 2006; Fothergill, 1996; Fothergill and Peek, 2004; Priestley and Hemingway, 2007; Bolin, 2007; Pomonis, 2002).

Other influences are the severity of the impact of each disaster, the effectiveness of initial responses, the quality of governance systems and the strength of the civil societies in which the events occur (Tierney and Oliver-Smith, 2012), as well as the pressure to make quick decisions with long-term consequences (Ingram et al., 2006; Olshansky et al., 2012). Overall, psychological recovery underpins broader social recovery and vice versa: the relationships between all aspects of recovery are reciprocal.

5.3.5.1 The psychosocial approach to disasters

Understanding the behaviour and the psychosocial and mental health needs of people affected by disasters is vital to disaster recovery because it affects how:

- societies, governments, communities and families prepare for disasters;
- responsible authorities work with communities to meet people's needs and preferences and ensure their continuing agency;
- governments and responsible authorities communicate with the public;
- the responsible authorities and agencies manage responses in the immediate, short and medium terms.

Patel (2014) identifies the gap between mental health specialists' use of the terms 'mental health' and 'mental disorder' and public conceptualisations of psychosocial suffering that affects many more people than those who require specialist mental healthcare. Thus, here, psychosocial refers to the psychological, social and physical experiences of people in the context of their social, cultural and physical environments.

5.3.5.2 The psychosocial and mental health impacts of disasters

There is a broad spectrum of ways in which people react emotionally, cognitively, socially, behaviourally and physically before, during and after a disaster. Research into these reactions has, however, identified some common psychosocial and mental health impacts (Box 5.10).

The majority of people are not likely to develop a mental disorder, but distress after emergencies is very common. In most cases, it is transient and not associated with dysfunction, and many people are psychosocially resilient despite their distress. People affected by large-scale events that destroy infrastructure may be immobilised by fear and hopelessness. In the immediate aftermath of most events, people behave in rational and altruistic ways, but the frequency of panic remains the most pervasive myth about disasters and is sometimes exaggerated in official policies (Carter et al., 2013).

Psychosocial resilience and trajectories of response

Social relationships have powerful influences on how people cope with disasters (Williams et al., 2014a). Most people recover reasonably well given social support from relatives, friends and acquaintances. Resilience is a dynamic process '… linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance' (Norris et al., 2009) and can be seen in differing trajectories of people's responses over time (Norris et al., 2009; Bryant et al., 2015; Fink et al., 2016) (Box 5.11).

Risk factors

Psychosocial impacts of disaster vary in severity with a number of factors, the most significant being the magnitude of the event and the degree of exposure to it, as well as gender, age, ethnicity, pre-existing psychosocial problems and the perceived quality of psychosocial support. Groups of people at greater risk of dysfunctional distress, social problems and mental disorders following disasters include: women; children and adolescents; older people; people who have pre-existing health problems and disorders; socially disadvantaged people; and staff of rescue and responding services.

5.3.5.3 Policies and interventions for psychosocial recovery

BOX 5.10

The psychosocial and mental health effects of disasters

Direct effects on people

1.Immediate and short term
   a. Short-term distress and dysphoria (a state of feeling unwell or unhappy)
   b. Acute stress reactions
2. Medium and longer term
   a. Persisting distress and dysphoria maintained by secondary stressors
   b. Grief
   c. Mental disorders (NB: these disorders are very frequently comorbid with each other)
      i. Substance use disorders
      ii. Adjustment disorders
      iii. Post-traumatic stress disorder
      iv. Anxiety disorders
      v. Depression
      vi. Impacts on personality

Direct effects of complicated, sustained and/or multiple events

1. Sustained distress and dysphoria that impacts on people's functioning
2. Exacerbation of existing mental disorders
3. Precipitation of new episodes of previous mental disorders
4. Increased frequency of new mental disorders

Indirect effects on people

Disasters increase medium- and longer-term psychiatric and physical morbidity because of their effects on social conditions that affect physical and mental health. These social determinants of mental health include:
1. Increased poverty
2. Changed social and societal relations
3. Threats to human rights
4. Domestic and community violence

Priority 4 of SFDRR calls on states 'to enhance recovery schemes to provide psychosocial support and mental health services for all people in need'. Indeed, the European Network for Traumatic Stress – TENTS (2008), which surveyed 33 European countries in 2007-2008, found planning and delivery of psychosocial care after disasters was suboptimal and inconsistent, with wide variations in plans and interventions. It concluded that more effective and evidence-based services were needed. In 2014, the Royal College of Psychiatrists in the United Kingdom drew together the NATO guidance (NATO, 2009) and the TENTS findings and guidance to produce a comprehensive approach to developing the quality of comprehensive policy, planning and practice for delivering psychosocial and mental healthcare for people affected by disasters — called 'OP94' (Williams et al., 2014a). The approach taken by OP94 builds on guidance from the Inter-Agency Standing Committee (IASC, 2008), WHO (2013), IFRC et al. (2009) and publications from McFarlane and Williams (2012) and Williams et al. (in press). Operationalising Psychosocial Support in Crisis (OPSIC), another initiative supported by the EU, has produced comprehensive guidance on psychosocial and mental healthcare in disaster settings to support harmonisation of approaches across countries. It is based on an extensive survey of research and practices (OPSIC, 2015).

Flexible, generic approaches are needed that can be adjusted as events and people's needs evolve. The NATO guidance (NATO, 2009), for example, is constructed around a strategic framework that contains components including the following.

- Constructing an evidenced knowledge base: appropriate knowledge provides a baseline for creating and implementing plans before events occur and adjusting them later.
- Working from core principles: identifying evidence-informed and values-based principles ensures lessons are learned from past events when planning, designing and delivering services:
- Gathering information: emergency specialists require services to gather and supply information to adjust generic plans as events evolve.
- Using a model of care: a model enables resources and services to be treated efficiently and effectively against people's assessed needs.
- Providing psychosocial care for the staff of all responding organisations: the needs of all responding organisation staff require active consideration.
- Incorporating psychosocial recovery and mental healthcare in an integrated emergency management cycle: using a single, integrated management cycle for all responses to disasters enables planners to design, deliver, review and adjust the services that the public requires.

The number of people who require

BOX 5.11

Trajectories of psychosocial and psychiatric responses

Resilient responses: around 70 % of people show psychosocial resilience. They suffer mild or moderate distress that rapidly reduces in severity if they receive support they perceive as adequate.

Deteriorating responses: initially, up to 20 % of people have stress symptoms of low severity, which become more severe and/or associated with dysfunction over time. About half recover later on, while others develop more chronic problems or disorders.

High initial stress responses: around 10 % of people may have high levels of stress before and/or immediately after events. The symptoms of about half may run a chronic course, while others improve.

The percentages in this box are approximations made from drawing together several different studies. They are only intended to illustrate broad orders of magnitude.

supporting psychosocial interventions to assist them with distress after disasters is very substantial. Early intervention and interagency coordination are vital elements in psychosocial responses. Williams and Kemp (2016) summarise the principles: intervening early can reduce the risks of survivors developing disorders later; there is a great deal that family members and friends can do in the response phases to alleviate people's suffering; families and communities are the main sources of emotional and tangible social support that people exposed to disasters prefer and receive.

Psychosocial recovery after disasters is a multidimensional process linked to measures that are taken before disasters occur, to the social and economic circumstances and to actions taken to restore assets and services.

Most people do not require specialist mental healthcare, but a substantial minority may. They require timely personal mental healthcare and a small proportion of them require long-term mental health services. Survivors at particular risk require surveillance and clinical assessment. OP94 provides a summary of specific components of the responding services that are required within the first week, first month, first to third months, and beyond 3 months after a disaster.

Psychosocial first aid, assessment and surveillance is needed for people who appear to be at risk of developing a mental disorder, and biomedical clinical treatments for people who have specific disorders. Psychosocial care offers people safety, calm, connectedness, hope and self-efficacy with the intention of promoting psychosocial recovery (WHO et al., 2011; WHO, 2013). Education, consultation and discussion processes for survivors, communities and responders also play an important role (Eyre, 2006; Aloudat and Christensen, 2012). Mutual support groups, such as Disaster Action in the United Kingdom, help survivors of disasters to come to terms with their experiences and loss and can also be a platform for action to improve safety and emergency management practice (Eyre and Dix, 2014).

In summary, research demonstrates that people's recovery in the short and medium term after disasters can be promoted through a psychosocial approach, using a strategic framework and generic policies that can be adapted as each disaster evolves. Psychosocial interventions can be made universally available to reduce suffering and risks of people developing mental disorders. Those with mental disorders can be supported through surveillance, assessment and effective, timely and sustained evidence-based treatments.

5.3.6 Conclusions and key messages

Partnership

Governance is key to reconstruction and recovery processes, particularly intergovernmental relations and public participation and engagement in post-disaster policies. Close collaboration across sectors and with affected groups is beneficial for physical, economic and psychosocial recovery processes. People and systems may not return to their pre-disaster state, but strong multisectoral pre-disaster plans and flexibility in response can help improve the speed and efficacy of recovery, avoiding indirect and adverse impacts after the disaster.

Knowledge

While the impacts of disasters have been well studied, recovery is multifaceted and not well understood. Significant progress has been made in understanding the psychosocial impact of disasters and on (re)construction techniques to improve the built environment after a disaster.

Innovation

Innovation in recovery promotion is particularly seen in reconstruction and more comprehensive approaches to rebuilding in urban areas. Given the diverse scales at which impacts are felt, more research is needed on the relationship between the different aspects of recovery, that is physical, social, psychological and economic.

5.4 Risk transfer and financing

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5.4.1 Risk financing and transfer: introduction and typology

Natural hazard risks can undermine development progress (UNISDR, 2015), financial and economic stability and well-being (World Bank, 2013). A sound financial protection strategy can lessen these impacts, speed up recovery and reconstruction, and harness knowledge and incentives for reducing risk (IPCC, 2012). Amidst growing damage and losses caused by natural and human-made hazards, some of which are further amplified by global environmental (including climate) change (IPCC, 2014), a comprehensive financial strategy is conducive to a better framed and informed risk management and governance.

The SFDRR (UN, 2015a) substantially reduced disaster losses and reinforced resilience as a top priority of international and national efforts. As part of the transformational change in how natural and human-made risks are dealt with (van der Vegt, Essens, Wahlström and George, 2015; Wahlström, 2015), the SFDRR emphasised investing in DRR and financing. The Addis Ababa action agenda on financing for development erected a financial framework that fosters inclusive economic prosperity and lines up financing resources and flows with the priorities of the 2030 agenda for sustainable development (UN, 2015b). Similarly, the Paris Agreement on climate change (UNFCCC, 2015) addressed the issue of promoting sound risk financing as part of climate adaptation and a strategy for coping with damage and losses.

A comprehensive disaster financing strategy is equally important in the context of the European Economic and Monetary Union. In the absence of financial protection tools for coping with disasters, the incidence of major disasters in several EU Member States may exacerbate economic imbalances and deteriorate credit ratings (S&P, 2015).

A comprehensive strategy for disaster financing can moderate the impacts of natural hazard risks, speed up recovery and reconstruction, and harness knowledge and incentives for risk reduction. Private financial sectors play an important role, along with governments and civil society organisations, in designing innovative financial protection goals and sharing knowledge and capacity.

A recent debt sustainability analysis showed that marginal changes in nominal GDP growth and interest rates can lead to a much greater debt-to-GDP ratio than the one projected as a baseline (EC, 2016). By targeting residual risk that cannot be efficiently mitigated, risk financing complements regulatory and economic instruments such as prices, taxes, tradable permits and liability (see Chapter 5.1), which serve as a vehicle of DRR and transition to a low-carbon, resource-efficient and socially inclusive economy.

Recognising that in an increasingly interconnected world disasters can have far-reaching, spill-over effects, the G20 finance ministers invited the Organisation for Economic Co-operation and Development (OECD) to develop a voluntary framework helping governments to develop financial strategies for disaster risk. The ensuing methodological guide (OECD, 2012) defines risk financing as strategies and instruments used to manage the financial impact of disasters, ensuring adequate capacity to manage and mitigate the costs of disaster risk, thereby reducing the financial burden and economic costs of disasters and enabling rapid recovery in economic activity (ibid.). A thorough understanding of risk exposure and risk-bearing capacity, as well as institutional arrangements creating favourable regulatory and market infrastructure are the major constituents of the comprehensive disaster financing strategy, along with the choice of optimal risk financing and transfer instruments.

Here we introduce various instruments, their design criteria and their principles, carrying institutions and markets, as well as the different public and private roles of their realisation. Disaster financing embraces a variety of instruments that are intended for and capable of achieving different outcomes. Each of these instruments can efficiently handle only a certain type of risk, depending on their frequency, intensity and impacts. Consequently, a strategy that builds upon a diversified pool of mutually complementing financial tools and institutions is better equipped to cope with and respond to a variety of environmental and human-induced risks.

Risk layering means pairing the suitability of different instruments with

TABLE 5.4

Major categories of risk financing and transfer instruments
Source: Adapted based on G20 (2016), GFDRR (2014), MCII (2009, 2013), Okuyama (2010), UFCCCC (2016), World Bank (2012)

Categories	Examples of instruments
Saving and reallocation	— bank deposits and liquid securities — reserve/contingency/disaster relief funds — budget reallocation
Credit and assistance	— contingent credit facilities and microcredit — fiscal relief such as delayed or reduced tax and social security payments — external assistance and aid
Insurance	— catastrophe risk insurance (from micro- to macro-insurance) — indemnity vs index-based vs modelled insurance schemes
Catastrophe-linked securities	— cat bonds (catastrophe bonds)
Derivatives	— weather derivatives

levels of risk and risk-bearing capacity (Mechler et al., 2014). The contingent losses from frequent, low-impact risk can either be reduced or retained through adequate funds in the form of savings, set-aside reserves or credits. Medium- to high-level risk exceeding the risk-bearing capacity can be more efficiently managed by risk transfer via insurance or capital markets.

Comprehensive risk management (MCII, 2013) embraces a systematic identification of risk arising from multiple hazards and employs a combination of financial instruments that take into account hazard exposure and risk-bearing capacity of (national and subnational) governments, homeowners, enterprises and the most vulnerable populations. In a more comprehensive way, the total climate risk approach, as adopted by the methodology of the Economics of Climate Adaptation Working Group (ECA, 2009), first explores manifold risks arising at a specific location or region today, then looks at the projected increase in risk due to economic development before finally considering the aggravation of risk due to a range of future climate change scenarios. The working group then devises and assesses a portfolio of infrastructural, technological, behavioural and financial investments to adapt to these risks. The various instruments (Table 5.4) differ in terms of access prerequisites, (opportunity) costs and activation time. This approach thus provides decision-makers with a fact base which enables them to understand the impact of weather and climate on their economy — and helps to identify actions to minimise that impact at the lowest cost to society. It therefore allows decision-makers to integrate adaptation with economic development and sustainable growth.

Disaster risk financing and transfer stretches out over several functions of responsible and accountable government, including fiscal (risk) and

TABLE 5.5

Disaster risk financing and transfer policy areas and benefits
Source: Adapted from World Bank (2014)

Sovereign disaster risk financing — Increases response and reconstruction capacity — Eases public expenditure by reducing volatility of disaster costs — Clarifies contingent liability — Provides incentives for investing in risk reduction	Property catastrophe risk insurance — Provides access to compensation for damage — Increases awareness of risk and understanding of financial vulnerability — Helps distribute risk and burden of recovery — Can incentivise investments in risk reduction
Disaster-linked social protection — Mitigates shocks by providing compensation for losses through safety nets — Increases awareness and understanding of vulnerability to disaster risk — Can incentivise investments in risk reduction — Safeguards vulnerable people from poverty	

budgetary policies, public finance, market and business development, and social protection (OECD, 2015; World Bank, 2014). Disaster risk poses implicit and explicit liabilities (Cummins and Mahul, 2009); explicit liability arises from statutory and contractual obligations, while implicit liability results from public expectations and political pressures. The latter poses the greater fiscal risk (World Bank, 2012). Governments play multiple roles, on both the demand and the supply sides of risk financing. As rule makers they: (i) provide public insurance and financing recovery and reconstruction expenses for public assets; (ii) organise (and cover the costs) of post-disaster order, rescue and relief; (iii) ensure social protection for vulnerable populations; and (iv) regulate and supervise financial markets (including insurance) and institutions. Nonetheless, only few countries have sought protection against fiscal impacts of disasters (World Bank, 2012).

The United Nations Environment Programme (UNEP), the United Nations Office for Disaster Risk Reduction (UNISDR); multilateral institutions such as the World Bank and the OECD, and other major actors have played a catalysing role for private sector involvement in DRR and financing. The UNEP's finance initiative, principles for sustainable insurance (PSI) (UN-FI 2012), and the UN-backed principles for responsible investment (PRI) have promoted sustainable lending, investment and insurance practices and sensitised nations to the environmental, social and governance challenges involved in business decision-making.
Other insurance-oriented initiatives, such as Global Insurance Industry Statements and the Climate Risk Statement of The Geneva Association, have urged contemplating climate risk in business investments and risk management strategies. More recently, a joint report by UNEP PSI and Inquire (Bacani, McDaniels and Robins, 2015) outlined three major initiatives: an Insurance Network on Sustainable Development to stimulate innovation and partnerships, a Sustainable Insurance Policy Forum to scale up intergovernmental cooperation and Insurance Development Goals to make the ways in which the insurance sector can contribute to meeting Sustainable Development Goals (SDGs) more explicit.

Similarly, international collaboration among financial businesses and financial regulators is growing, focused in large part on knowledge sharing and capacity building. The Financial Stability Board (FSB) convened a Task Force on Climate-related Financial Disclosures (TCFD, n.d.) focusing on disclosing market-relevant information on climate-related financial risk, the results of which were released in December 2016 (TCFD, 2016). The International Capital Market Association (ICMA) has coordinated the development of the 'green bond principles', which have helped catalyse the rapid growth of the green bond market (G20, 2016).

5.4.2 The role of insurance: spreading risk

Insurance is the most common form of financial protection against risk of contingent losses. The insured party or policyholder transfers the cost of potential loss to the insurer in exchange for monetary compensation known as a premium. By acquiring the costs of contingent losses from many policyholders, the insurer absorbs, pools and diversifies the individual risks, making them assessable and manageable.

Insurance is the most common form of financial protection against risk of contingent losses. But not all risks are insurable or covered by insurers. Climate change amplified natural hazard risks, and raising vulnerability may make financial protection unaffordable for some people and business, and risks uninsurable in certain places.

When the loss occurs from specified contingencies under an insurance contract, the insurer indemnifies or compensates the insured party. The premium charged should reflect the level of risk each policyholder cedes to the insurer. The premium will reflect not only the 'pure premium', i.e. the average losses expected from the contract, but also allowances for expenses and the contract's impact upon the insurer's capital requirements (and so its required contribution towards target return on capital).

Not all risks are insurable or covered by insurers. Insurable risks are those that are quantifiable, in terms of both the probability of an event's occurring and the extent of losses incurred, and for which premiums can be set for each policyholder or group of policyholders (H. C. Kunreuther and Michel-Kerjant, 2007).

In addition, risk ambiguity, asymmetry of information (implying adverse selection and moral hazard) and correlation between losses influence the ability and willingness of insurers to underwrite risk and the level of premium sought (Charpentier, 2008; Jemli, Chtourou and Feki, 2010; Louaas and Goussebaile, 2016). If the latter are high, risks may be insurable but not affordable for low-income subjects who may benefit most from insurance.

Natural hazards that have been amplified by climate change may make financial protection unaffordable for some people and risks uninsurable in certain places. Recent estimates of the Bank of England (PRA, 2015) show that climate change and socioeconomic risk drivers may widen the gap between 'affordable' flood insurance premiums and premiums that reflect the technical price of flood insurance. Likewise, Kunreuther et al. (2011) demonstrated that climate change is likely to significantly increase premiums for building insurance in Florida. These studies also suggest that consistent risk reduction efforts may be effective in keeping premiums affordable. A better understanding of risk, product bundling and public interventions (see Chapter 5.4.4) contributes to making climate risk insurable.

Insurance is a financial service offering protection against the risks of contingent losses. However, directly or indirectly, it also serves other purposes. By facilitating prompt post-disaster recovery, insurance helps to contain the economic and social impacts of disasters. Beyond that, insurance serves public interests by promoting social protection and public welfare. Insurance makes it possible, for example, for individuals to get mortgage loans or compensation for injuries without going to court (Talesh, 2012). Insurance can also promote numerous economic activities in the higher risk/return market spectrum (Grant, 2012), thus contributing to higher productivity and innovation. And it can incentivise behaviour change and individual risk prevention, as shown in Chapter 5.4.3.

BOX 5.12

Role of insurance for better understanding of risks

The reinsurance industry has driven the development of catastrophe risk analytics over the last 30 years, moving from a position where hazard mechanisms, their impact and comparative risks were little understood, to one where sophisticated and integrated stochastic catastrophe models have become the norm in the industry. The models require and understanding and knowledge of:

- the likely hazard events, that is their frequency, severity and geographic scale;
- the buildings/goods insured, that is where they are, how they are built and how they are used;
- the vulnerability of these buildings/goods to the events;
- the financial/social loss caused.

The process of building and understanding these models, as much as the model results themselves, has lead to a transformation of the insurance and reinsurance industry, massively increasing technical understanding and financial resilience. The appropriateness of these modelling techniques, the ability of the models to provide objective rigour around risk mitigation and adaptation decision-making and the benefits of the consequential greater risk and hazard understanding are leading many governments and quasi-government organisations to consider adopting these methods. A catastrophe insurance scheme can be a catalyst to great risk understanding.

A variety of insurance schemes exists, depending on the type of risk and the protected asset (property, business assets and interruption, liability, sovereign risk, etc.). Natural hazard insurance is either an extension of property insurance (Bräuninger et al., 2011) or a stand-alone, for example agricultural (crop yield, revenue or income) and energy insurance. Sovereign insurance (Mahul and Ghesquiere, 2007) covers costs associated with damage to infrastructure and relief expenditure. Traditional insurance employs the principle of indemnity, claim payments are made to make good an actual loss ether in full or in part. However, indemnity insurance requires a thorough knowledge of the good(s) insured, how they react to a certain hazard and a post-event assessment of damage incurred, all adding to expense and delays in claim settlement. Parametric or index insurance schemes employ other, more easily measurable data (for example rainfall, yields or vegetation index) for determining pay-offs without the need to prove actual loss, requiring less detailed knowledge of the risk covered and enabling speedy payment (Collier et al., 2009; Hazell et al., 2010; IFAD and WFP, 2011).

Agriculture poses particular challenges for insurance because of the spatially correlated weather and climate risks and large information asymmetries (Porth and Seng Tan, 2015). Agricultural insurance schemes differ from country to country but often involve the public sector (Bielza et al. 2009; Capitanio, Bielza, Cafiero and Andolfini, 2011), either via premium subsidies or public participation in reinsurance systems. Insurance products can be classified according to the risks covered (named perils and multiple perils) and trigger of claim (e.g. indemnity or index based, crop revenue and farm income) (Iturrioz, 2009). More sophisticated insurance schemes include comprehensive income/revenue insurance packages also covering, besides production, market risks (e.g. price), although most insurance policies limit their coverage to yield variability risk (including single risk, combined, integral insurance and whole-farm integral insurance) unless the market risk can be transparently hedged in the commodities market. In the EU, farm risk management schemes are supported, among others, through rural development programmes (Bardají et al., 2016; EC, 2013c).

Based on 2015 data, the European insurance industry holds the largest share (32 %) of the global market (Insurance Europe, 2016). Property insurance accounts for about 8 % (around EUR 93 billion) of written premiums and 6 % (EUR 53 billion) of claims paid. Insurance coverage is very heterogeneous across the EU Member States and hazard types (A. M. Best, 2016; Maccaferri, Carboni and Campolongo, 2012). For natural hazard, some countries apply a free market system, others a centralised national or state scheme and others again an amalgam of public and private schemes. For example in the United Kingdom, natural hazard insurance is written competitively by private insurers, although with optional state-supported reinsurance for hazardous flood risks to ensure affordability. In contrast, in Spain, standardised natural catastrophe cover is provided by a public national pool.

On average over the period 1980-2015, out of the total registered natural hazard losses in Europe the share of those insured amounted to 30 % (EEA, 2015). Globally, written premiums in agriculture amount to around EUR 27 billion, an approximately fourfold increase since 2005 (Porth and Seng Tan, 2015).

In 2013 and as part of the EU Climate Adaptation Strategy package (EC, 2013a), the European Commission launched a broad consultation about which EU action could be appropriate for improving the performance of insurance markets (EC, 2013b). The responses cautioned against uniformising the regulation on natural hazard insurance across the EU (EC, 2014). Both the uneven distribution of hazard risk and the diversity of the economic standing and other requirements of customers have been brought up as reasons against an EU intervention (HM Treasury, 2013). Consequently, uniformised regulations could harm innovation and competition in insurance products. The European Parliament stressed that flexible markets should operate in a non-mandatory framework and that no 'one size fits all' solution would serve the magnitude of different risk and economic conditions in Europe (EP, 2014).

5.4.3 The role of insurance: incentivising risk reduction

Insurance can help dissuade policyholders from risky behaviour and incentivise risk reduction (Surminski and Oramas-Dorta, 2013; Surminski, 2009; Warner et al., 2009). Premiums and policy terms (e.g. deductibles) can be adjusted to reward good risks and penalise bad ones. The role that the insurance industry has played in deploying loss-prevention technologies such as automobile air bags and fire prevention/suppression systems is an example. Harnessing insurance for DRR becomes particularly significant in the context of increased frequency of disaster events, larger economic exposure, rising vulnerability and climate change.

Insurance and other financial instruments can contribute to reducing disaster risk, if designed and implemented to this end.

There is an ample consensus that insurance can and should play an increasingly important role in mitigating disaster impacts, not only through risk sharing, but also through all aspects of the risk management cycle, including risk identification and modelling, risk awareness, damage prevention, risk transfer and recovery (Michel-Kerjan and Kunreuther, 2011; Evan Mills, 2012; Swenja Surminski, 2014). However, practical evidence of whether insurance encourages risk reduction in a climate context remains inconclusive (Botzen and van den Bergh, 2009; E. Mills, 2009; Surminski and Oramas-Dorta, 2011; Surminski et al., 2015). Few existing national catastrophe insurance schemes directly include risk reduction incentives (Swenja Surminski and Oramas-Dorta, 2014; von Ungern-Sternberg, 2004). Nevertheless, progress is being made. Insurers are increasingly rewarding customers who take steps to reduce their risk with lower premiums (or avoid the risk if they do not). The regional natural catastrophe scheme, African Risk Capacity (ARC), mandates that clients, in this case African countries, undergo a period of risk analysis and policy design with ARC staff before they are allowed to buy a policy. Countries are also required to agree contingency plans to put in place in the case of loss and agree a revised final implementation plan when a loss occurs.

Existing studies, such as Thieken et al. (2006) in Germany and Poussin et al. (2013, 2015) in France, rely on isolated surveys of insured and uninsured parties. Whilst they suggest that insured parties are slightly more likely to undertake risk reduction efforts than uninsured ones, there are some methodological issues that limit comparability and scalability. Survey response methods often suffer from fundamental problems of reliability and internal validity, and even when considered sufficiently robust, they offer no consistent and comparable method for assessing the cost-effectiveness of insurance mechanisms. Hudson et al (2014) found that those buying natural catastrophe insurance are particularly risk averse, which suggests that the higher observed risk reduction of the insured may be an effect of selection.

Measuring if and how insurance contributes to direct risk reduction remains challenging, as it requires an understanding of disaster impacts and the scope of risk prevention measures that are induced by insurance, including measures influencing the policyholder's behaviour, directly promoting actions by the policyholder and directly or indirectly affecting actions by third parties (such as the government). Various metrics for assessing the insurance impact on promoting risk reduction/prevention have been proposed in the literature, including Chrichton (2008), Paudel et al. (2012), Surminski and Oramas-Dorta (2013)and Surminski and Eldridge (2015). In the latter study, elements of this approach were applied to United Kingdom flood insurance schemes through a set of qualitative assessments.

Recently, attention has been brought to harnessing insurance for better protection of the environment as well as ecosystem services for the sake of DRR. Ecosystems may mitigate natural hazard risks by mediation of flows and nuisances or through maintenance of physical, chemical and biological conditions in the face of pressures. Ecosystem services for DRR are most frequently associated with mass stabilisation, water flow regulation (especially flood control), wind dissipation and (micro- and regional) temperature regulation. Other equally important hazard-mitigating services include control of pests, disease and alien species, water filtration, and dilution and detoxification of hazardous substances. The combination of increasing intensity and frequency of natural hazards, continuing conversion, uniformisation and simplification of (semi-)natural ecosystems and the footprint of built infrastructure may be contributing to the rapid increase in costs and damage from natural hazards. The European Commission research and innovation policy agenda on nature-based solutions (EC, 2015b) defined 'insurance value of ecosystems' as a 'sustained capacity of ecosystems to reduce risks to human society' caused by natural hazards, climate variability and climate change. The insurance value of ecosystems in this sense is equivalent to the net present value of avoided damage and losses obtained from the risk mitigation ESS. In other words, it is the monetary value that risk reduction by ecosystems would bring to risk transfer schemes such as insurance. One indicator could be a reduction in property insurance premiums in light of reduced risk; another could be the willingness of the private sector to underwrite a risk on the basis of confidence in ecosystem services.

Collective insurance schemes appear better equipped to deliver sizeable improvements of ecosystem services and to get around concerns about free riding. An example of a collective insurance reward under a state-subsidised insurance scheme is the Community Rating System (CRS) under the United States National Flood Insurance Program (NFIP), where households receive a premium discount if their community takes specified flood-mitigation measures; which can include nature-based solutions. Pollution insurance provided to businesses is another example of a positive relationship between taking out insurance and reducing harmful environmental damage (Surminski, 2015). A 2003 OECD study found that, with pollution insurance, the insurer may act as a private surrogate regulator aligning its interests with those of high environmental standards (OECD, 2003). More than that, properly priced insurance can help to internalise externalities (such as environmental risks) and hence improve or even secure more sustainable functioning of markets. The internalisation of environmental costs through the payment of premiums is compatible with the deterrence goal of any liability regime and with 'the polluter pays' principle. Conversely, Minoli and Bell (2003) found in an evaluation of two leading United Kingdom insurance companies' pollution claims that the insurers' initial underwriting assessments and post-loss investigations were insufficiently developed. The management practices of insured parties in connection with the prevention of pollution were also underdeveloped. Consequently, insurers' terms and conditions on policies were insufficient to work as an incentive to dissuade pollution losses.

The effectiveness of environmental insurance has been most extensively researched in the United States. For example, there is evidence that despite a range of practical barriers, environmental insurance can be efficient where government fines are not (Yin et al., 2011). The concept of liability for environmental damage, instituted in Europe by Directive 2004/35/CE (EC, 2004a), extended the law of tort to damage incurred to ecosystems. The directive points to sureties or bank guarantees but leaves it to Member States to guarantee financial solvency for damage rectification and clean-up. In the wake of this directive, insurers have developed data sets to map ecosystems and their characteristics with a view to facilitating restoration in case of accidental damage through an insured entity. This development points to a possible entry point for the more widespread incorporation of ESS concepts in an insurance.

5.4.4 Public–private partnerships for risk financing and transfer

A commercial insurance may not guarantee affordability and equitable access to insurance (EC, 2013b). Addressing affordability and equity issues in provision of disaster risk insurance combines business objectives with public policy goals (Solana, 2015). Consistently, the role of the public sector in this pursuit goes beyond the regulatory oversight to include an active involvement in insurance provision. Because public intervention may interfere with market equilibriums and undermine rather than encourage individual risk reduction (Surminski, 2009), reconciling the public and private roles and objectives necessitates a thorough analysis and organisation (Pérez-Blanco and Gómez, 2014).

'Public–private partnerships' (PPPs) is a term coined to denote different approaches to public and private cooperation for providing public services or projects (Bielza et al., 2009; CEA, 2011). PPP is a model for a joint bearing of responsibilities and efficient risk sharing intended to increase insurance coverage and penetration and guarantee a strong financial backing in view of uncertain tail distributions of risk (Johansen, 2006). PPPs are typically characterised as a long-standing relationship bringing forth mutually beneficial resource and risk-sharing arrangements (EC, 2004b).

Ideally, the PPPs should be designed so as to address market failures such as a lack of or a limited access to affordable insurance and low insurance penetration. In doing so they should limit, to the extent possible, market distortion and preserve competition. Private insurers (should) 'have the opportunity to carry on using their savoir faire in an environment of mutual understanding' (Johansen, 2006). The PPPs should be shaped through constructive dialogues and conscious of mutual principles and limitations. The partnerships should actively promote or at least not harm the incentive for risk reduction, for example by making the individual insurance costs reflecting those risks that result from each individual's choices (Mysiak and Pérez-Blanco, 2016). They should be built on principles of transparency, equal treatment and efficient use of public resources.

In Europe, the most longstanding insurance-related PPP is embodied within the extraordinary risks insurance scheme of Spain's Insurance Compensation Consortium (Consorcio de Compensación de Seguros - CCS). Instituted in 1954 after its provisional creation in 1941, the CCS is an independent public company attached to the Ministry of Economics, Industry and Competitiveness but with separate accounts and a certain degree of entrepreneurial freedom (CCS, 2016).

As a tool at the service of the Spanish insurance sector, CCS performs many different functions, among others the lynchpin of the Spanish Extraordinary Risk System. The extraordinary hazards covered are well defined in the statutes and include floods (before 1986 conditional on declared catastrophe zone, Barredo et al., 2012); cyclones, tornadoes and wind storms (with gusts exceeding 120 km/h); earthquakes; tidal waves; volcanic eruptions; meteor strikes; and other hazards such as acts of terrorism and civil unrest. Spain counts additionally with a comprehensive combined agricultural insurance, managed by a pool of private companies (Agroseguro) in which CCS participates both as a co-insurer and as a reinsurer. A bulk of the estimated EUR 6.4 billion paid in compensations over the 1987-2014 period referred to floods and windstorms (Espejo Gil, 2016).

Public–private partnerships (PPPs) are a model for a joint bearing of responsibilities and efficient risk sharing, capable of increasing insurance coverage and penetration and guaranteeing a strong financial backing in view of uncertain tail distributions of risk.

The scheme is financed by compulsory surcharge on designated insurance policies. Insurance policies covering property damage (with some exceptions), business interruption and personal life and accident.The flat rate surcharge is based on the total insured value and varies only across the type of underlying insurance policies. For example for dwellings and office building the surcharge amounts to 0.008 per thousand.The same rate applies without differentiation for any degree of exposure and any risk across the entire country, as it is calculated considering all claims and risks covered as a whole. Deductibles are applied to commercial policyholders but not to households (ibid.). Risk underwriting is the task of private insurers and the extraordinary risk cover is entirely transferred to CCS. In exchange, the insurers retain 5 % of the collected surcharges to cover administrative costs. Claims are managed and indemnified by CCS. The fact that the scheme has very low administrative costs (less than 10 % of the collected surcharges including the costs of claim processing) is an argument in favour of this arrangement (von Ungern-Sternberg, 2004). Half of the CCS Board of Administrators is composed of chief executive officers from Spanish insurance companies and the other half of senior officials of the public sector. All decisions affecting CCS or the Extraordinary Risk Coverage System emanate from the board, setting another example of PPPs, which is also a flexible mechanism to easily introduce modifications to the system.

France introduced the 'Catastrophes naturelles' (CatNat) insurance regime back in 1982 in the aftermath of the devastating Saône, Rhone and southwest France floods (CCS, 2008; Magnan, 1995). It is based on a mandatory extension of insurance policies against fire and damage to property (theft, water damage, etc.) and land vehicles, to protect also against damage caused by extreme natural hazard events deemed uninsurable. A defining characteristic of the CatNat regime is that the exceptional character of the natural hazard events, serving as a trigger for damage compensation, has to be sanctioned by an interministerial decree. What qualifies as natural disaster is not exactly specified by statutes and is indeed sanctioned case by case. The CatNat system usually applies to floods, landslides, subsidence, droughts, avalanches, earthquakes and tidal waves. CatNat exemplifies a system in which policyholders cannot exclude the natural hazard coverage, and the insurers have to supply it (Grislain-Letrémy et al., 2012). The additional premiums (or surcharges) are set by the government as uniform percentage rates of the underlying property insurance premium without any regional differentiation, equal for all risks covered and any degree of risk exposure. The government also determines the level of deductibles that are compulsory even if the underlying (base) policies do not envisage them. The deductibles serve as an incentive for risk prevention: the policyholders in districts without a risk prevention plan (Plans de Prévention des Risques - PPR) have to accept higher deductibles when exceptional events of the same hazard types occur consecutively (von Ungern-Sternberg, 2004). In addition, a levy on the CatNat premiums flows into aFund for the Prevention of Major Natural Hazards (Fonds de Prévention des Risques Naturels Majeurs - FPRNM), which finances prevention measures.

Private insurers underwrite the risk, collect premiums and process the claims. Except for the premium rates and deductibles, the natural disaster cover follows the terms and conditions of the underlying insurance policy. The insurers may choose to reinsure the underwritten risks by a Central Re-insurance Company (Caisse Centrale de Réassurance - CCR), initially a public entity of commercial nature and later turned into a state-owned limited company. The CCR offers two types of complementary and inseparable reinsurance contracts: (i) quota-sharing contracts under which the CCR accepts a share of the risk in exchange for a share of the collected premiums; and (ii) stop-loss contracts under which the CCR compensates the loss that exceeds the insurer's annual premium income by a certain factor (OECD, 2014). The CCR holds a dominant position in the reinsurance market in France (Grislain-Letrémy et al., 2012). In 2015 the French Insurance Federation (Fédération Française de l'Assurance - FFA), estimated that by 2040 the human induced climate change may increase the disaster losses by 90 % (EUR 44 billion) compared to losses over the past 25-year-long period (FFA, 2016a). To improve the sustainability and viability of the CatNat regime, the FFA made several suggestions about how to make DRR an integral part of the regime. Among other things, the FFA recommended that the insurers should be able to define the level of deductibles for major policyholders (with insured value beyond EUR 50 million) (FFA, 2016b).

The Flood Reinsurance Scheme (FR Scheme or Flood Re (n.d.)) in the United Kingdom is an example of a public–private reinsurance mechanism for flood components of housing policies. Private flood risk insurance in the United Kingdom has a long tradition and coverage of residential properties is among the highest in Europe (Maccaferri et al., 2012). Housing insurance typically covers a portfolio of risks in addition to floods and is compulsory for securing mortgage loans. Public–private cooperation in the flood insurance sector started in the 1960s and gradually evolved into a partnership entailing tangible commitments on both the public and private ends (Penning-Rowsell et al., 2014; Ball et al., 2013; Lamond, Proverbs and Hammond, 2009; Penning-Rowsell and Priest, 2015).

The FR Scheme had been designed as a publicly accountable but privately owned and managed, non-profit service organisation. The ownership and management of the scheme is entirely in the hands of the insurance industry, with a limited government membership role. The commercial insurers are free to choose whether to reinsure the written market risk or cede the flood-risk component of housing policies to the scheme at predetermined, capped prices. In the latter case, any and all damage claims are paid by the scheme and the primary insurers continue acting as a broker. The capped premiums are specified by the regulation (FR Regulation, 2016), annually updated by the consumer price index and revised every 5 years.

The FR Scheme is funded by an annual statutory levy set at GBP 180 million (EUR 213.5 million) for the first 5-year period, which is imposed on all home insurers operating in the United Kingdom. The total amount of the primary levy was decided as an equivalent level of current cross-subsidy, which amounts to an estimated GBP 10.5 (EUR 12.5) per household. The FR Scheme administrator can raise supplementary (top-up) levies or contributions in cases where it does not have sufficient resources to meet its non-reinsured claims.

Because the statutory and top-up levies constitute a state aid and the scheme entails a selective advantage, the European Commission had been notified and reviewed the FR Schemes. In its review, the Commission recognised the goal of ensuring affordable insurance against flood risk as a legitimate aim of public policy (EC, 2015a). Furthermore, it recognised that the FR Scheme promotes a free flood insurance market and rectifies market failures that might or eventually would compel insurers to stop providing insurance cover in some areas or only at high prices that would not be affordable by all households. Neither of these outcomes was deemed acceptable. The Commission acknowledged that the FR Scheme was designed in such a way as to minimise the (competitive) advantage granted to the insurers, and that the threshold above which the insurers will be able to cede the premiums to the Flood RE scheme will be attuned in a way that limits market intervention to only around 2 % of domestic insurance policies. Other design criteria have prompted a positive review of the scheme. The fact that the capped premium is differentiated by the Council tax band and is adjusted to inflation made the scheme proportional to its objectives. More importantly, the scheme is designed as a transitional measure to be phased out after 20-25 years. While the Government has publicly committed to continue flood risk defence efforts, Flood Re does not provide any incentives for risk reduction and resilience, which has been highlighted as a problem for ensuring future affordability and availability of flood insurance. (Surminski, 2017; Jenkins et. al. 2017).

5.4.5 Conclusions and key messages

Partnership

A comprehensive strategy for disaster financing can moderate the impacts of natural hazard risks, speed up recovery and reconstruction, and harness knowledge and incentives for risk reduction. Private financial sectors play an important role, along with governments and civil society organisations, in designing innovative financial protection goals and sharing knowledge and capacity. PPPs are a model for a joint bearing of responsibilities and efficient risk sharing, capable of increasing insurance coverage and penetration and guaranteeing a strong financial backing in view of uncertain tail distributions of risk.

Knowledge

Climate change has amplified natural hazard risks, and raising vulnerability may make financial protection unaffordable for some people and businesses as well as risks uninsurable in certain places. Insurance and other financial instruments can contribute to reducing disaster risk, if designed and implemented to this end. The reinsurance industry has driven the development of catastrophe risk analytics over the last 30 years, moving from a position where hazards mechanisms, their impacts and comparative risks were little understood to one where sophisticated and integrated stochastic catastrophe models have become the norm in the industry.

Innovation

Insurance can help dissuade policyholders from risky behaviour and incentivise risk reduction. Premiums and policy terms (e.g. deductibles) can be adjusted to reward good risks and penalise bad ones. Harnessing insurance for DRR becomes particularly significant in the context of increased frequency of disaster events, larger economic exposure, rising vulnerability and climate change. Comprehensive strategies for risk financing help to shed light on impacts of disaster risk on economy and society and facilitate identification of actions to minimise them. They allow decision-makers to integrate adaptation and risk reduction with economic development and sustainable growth.

Recommendations

National policies for disaster prevention and mitigation involve cooperation across sectors and scales. Partnership for mitigation and prevention is particularly important — there is a need for active engagement and commitment of the private sector, communities and academia as well as a need to share responsibilities for development and implementation of DRM strategies. Nevertheless, the main responsibility will remain with national governments, as also reaffirmed in the SFDRR. Some further efforts will be required in order to ensure that DRM is considered a cross-sectoral topic, which requires engagement and commitment on behalf of multi-stakeholders. Understanding direct and indirect costs is crucial to selecting and investing in preventive measures as well as the stakeholders to be involved and their roles and responsibilities.

However, identifying suitable investments is not enough; presenting evidence of additional dividends to policymakers and investors could provide a narrative reconciling short- and long-term objectives, thereby improving the acceptability and feasibility of DRM investments and enhancing the business case for investment in prevention and mitigation.

Integration of mitigation and prevention policies and regulations is a key innovation in mitigation and prevention, but it is rare. Where zoning regulations, building codes and insurance policies are integrated, the mitigation strategy becomes more coherent and easier for stakeholders to implement.

Cooperation between regional, national and international communities is particularly important for preparedness and response planning given the transboundary nature of modern-day disasters. ELSI are not a separate dimension of DRM that can be addressed in isolation. Good preparedness can protect societies from exceptions that go against ordinary morals, integrity and dignity, from unintended consequences and from entrusting decisions solely on experts or governments without public engagement.

A move away from command-and-control approaches to managing disasters has opened up more opportunities for citizens to participate in preparedness and response. Strong bonds and trust within and between communities favours a more effective response in emergencies and can be harnessed by authorities. Social media can also be used to enhance self-organised mobilisation and coordination of local resources, knowledge and efforts for disaster preparedness and response.

Close collaboration across sectors and with affected groups is beneficial for physical, economic and psychosocial recovery processes. Recovery is complex and people and systems may not return to their pre-disaster state, but strong multisectoral pre-disaster plans and flexibility in responses can improve the speed and efficacy of recovery, avoiding indirect and adverse impacts after the disaster.

Significant progress has been made in understanding the psychosocial impact of disasters and on (re)construction techniques to improve the built environment after a disaster. Scientific gaps still remain in understanding economic recovery given the diverse scales at which impacts are felt and potential problems created by external intervention for local economies post-disaster.

Innovation in recovery promotion is particularly seen in reconstruction and more comprehensive approaches to rebuilding in urban areas.

A comprehensive strategy for disaster financing can moderate the impacts of natural hazard risks, speed up recovery and reconstruction and harness knowledge and incentives for risk reduction.

Climate change has amplified risks and raising vulnerability may make financial protection unaffordable for some people and businesses as well as risks uninsurable in certain places.

Insurance and other financial instruments can contribute to reducing disaster risk if designed and implemented to this end.

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5.4 Risk transfer and financing

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Chapter 6

Future challenges of disaster risk management

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6 Future challenges of disaster risk management

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CONTENTS

Introduction

The work of summarizing knowledge in disaster risk management is not only to communicate what we know. It is equally important to recognize what we don't know. Knowledge gaps, once identified, can be addressed by future research and development projects.

We've asked all lead authors and coordinating lead authors to critically look at their fields of expertise and identify the future challenges. Some relate to forming the right partnerships. Other challenges are about creating new knowledge - the classical research projects. A third category of challenges are about applying new knowledge, i.e. innovation. This bottom-up approach brought to light a wide spectrum of future challenges and emerging issues.

This chapter provides a summary of these key messages to various reader communities on the key challenges: all DRM actors, scientific experts, policymakers and practitioners.

ALL DRM ACTORS

Partnership

- The Sendai Framework signals a clear mandate to the science, technology, and innovation community to work together with governments in developing and sharing the knowledge and solutions needed to improve the resilience of communities. **Stronger partnerships** among disaster risk science, policy and practice are necessary. The benefits of collaboration are recognized throughout this book by all three communities.

- To tackle **systemic challenges** related to disaster risk reduction, a **transdisciplinary and holistic approach** in is necessary involving science, policy makers and practitioners. Resilience building needs to start at the level of **individual households and communities**. Partnerships are particularly useful for **building awareness** of available knowledge in the communities and build trust to exchange experiences, skills and knowledge.

- Scientists, practitioners and policy makers must work together to create **evidence-based narratives** for reconciling short- and long-term objectives of risk management, such as economic and social benefits, in order to enhance the business case for investment in prevention and mitigation.

- There is a need for **dedicated platforms** at local, regional, national and international level for science-policy-practice interface adapted to the local context. These platforms need to link and cooperate.

Knowledge

- Two key challenges in the scientific world are increased complexity and acceleration. Ever more science is produced and is available at a mouse-click. Ever more actors from different disciplines and policy areas are involved. For practitioners, policy makers and even for scientists themselves, the challenge now is to **find the relevant science**, from multiple disciplines, and make sense of it, for multiple policies.

- A fundamental building block is **understanding the risks** being faced; as well as making sense of the relevant science this also requires enhancing the **use of local knowledge**.

- In such a complex policy area, **knowledge management** is essential. Relevant science must be synthesized for different target audiences. Science must be made available in useful format.

- Knowledge is not only the realm of scientists. Evidence in evidence-based policy making is much wider than scientific knowledge only. **Experience of practitioners** must be collected and fed back to scientists (for analysis) and policy makers.

Innovation

- The main areas for innovation lay in **risk governance**, including better communication among the communities, engagement and clear roles for all actors, and accountability and transparency throughout the system. The **interface between scientific knowledge and pragmatic decision making** must continuously be improved, e.g. through secondments of scientists into government and vice versa.

- Practitioners can benefit from many **unexploited research results**. Hurdles for innovation must be tackled through training, exercises, demonstrations, pilot projects, etc.

- **Vast amounts of data** are being produced from many sources – e.g. earth observation is expected to bring 10TB of free and open data per day. New approaches are needed for data handling and processing. Early warning systems (EWS) play an important role in saving life and property and should benefit from the **data revolution** combined with more robust modelling in order to help reduce the time required for the warning activation and improve the warning information.

SCIENTIFIC EXPERTS

Partnership

- **Synthesis of scientific knowledge** across disciplinary boundaries requires the development of networks where mutual learning can happen and trust can be built. It is important to be transparent on context, terminology, assumptions and limitations.

- To tackle **systemic challenges** related to disaster risk reduction, a **transdisciplinary and holistic approach** in science is necessary to integrate natural, social and health sciences with ICT, economics, engineering, legal and policy frameworks and operational practice. A shift from mono-disciplinary silos to transdisciplinary networks is required but challenged by differences in risk frames, objectives, terminology, methods and funding mechanism.

- Science needs to produce **coherent advice**, during emergencies and for long term risk management. **Pre-established mechanisms to access scientific experts** from all disciplines are necessary for effective risk governance. Scientist must be ready to engage with such mechanisms, and translate their expert knowledge for non-technical communities. For emergencies, **impact-based multi-hazard early warning systems** must be developed to assess the likely impact of any hazard on population, economy and society.

- **Partnerships should be effective**. Measuring the effectiveness of partnerships is a scientific challenge in itself. Social network analysis and other techniques should continuously monitor the effectiveness of partnerships, including their depth, reach and growth, connectivity to other networks, scientific innovation and impact on policy and practice.

Knowledge

- This report shows that a wealth of knowledge exists, but each discipline still has its own scientific challenges. For instance, **natural sciences** seek to improve modelling of bio-physical processes of the Earth and atmosphere to anticipate extreme events for early warning and under climate change. **Engineers** must keep improving standards, cost-benefit methods, green and gray prevention solutions, retrofitting and other engineering challenges. **Social scientists** should better understand decision making under uncertainty, improve risk communication theory, harness social networks and include ethical and legal issues. Measuring effective risk governance (including ethical and legal issues) is an outstanding challenge, as are assessing science-policy interfaces and metrics for the impact of science on DRR. **The information communication technology** (ICT) community must harness rapidly developing technology, including big data, artificial intelligence, and augmented reality for better human-machine interaction. **Economists** see further challenges in disaster financing, including loss estimations, cost-benefit methods and understanding economic recovery, given the diverse scales at which impacts are felt and potential problems created by external intervention for local economies post-disaster. **Health sciences** should be more involved in the DRM community, advancing their understanding of outbreaks and pandemics, health impacts of all hazards, but also advances in data collection.

- **Transdisciplinary research** is in its infancy and should be encouraged. The most difficult challenges in disaster risk management cannot be solved by a single discipline. Specific challenges identified in this report include better handling of **uncertainty**, a more coherent approach to **data** across disciplines (open data, big data, social data) balancing openness with privacy, development of science-based **standards and guidelines**, and development of **methodologies** for all-risk mapping and management.

- There is a clear need for more **systematic knowledge management**. Access to synthesised knowledge of other disciplines is important for scientists, practitioners and policy makers.

Innovation

- More innovation is needed in in-situ, sea-borne, air-borne and satellite sensors to increase the completeness and timeliness of **earth observation**. Scientists help develop better, cheaper and robust instrumentation, allowing pervasive deployment also in poorly monitored areas, which should yield the necessary data to drive new scientific developments. Similarly, scientists must develop and exploit social networks to gather **fine-grained**

socio-economic data on vulnerability and resilience of people, communities, economies and societies. More **technological innovation** is necessary to enable "total conversation" among citizens and authorities.

- A comprehensive strategy for **disaster financing** can not only moderate the impacts of natural hazard risks, it can speed up recovery and reconstruction, and harness knowledge and incentives for risk reduction. More research is needed on how these incentives could work more effectively.

- To foster adoption by public authorities, technological innovations must be **tested and demonstrated** to end-users with clear criteria for evaluation. The policy-impact of innovations need to measured and, if relevant, mechanisms for **institutionalizing innovations** are necessary. It is challenging to make **global solutions available at local level**.

- **Fostering innovation** involves all actors, including funding agencies, researchers, practitioners and policy makers.

POLICYMAKERS

Partnership

- **Continuity of partnerships** is particularly challenging. As interlocutors both on policy maker side (rotation) and scientific side (projects end, new projects start over) change often, there is a continuous learning curve. Establishing well-funded, long term partnerships may be beneficial.

- A partnership should first agree on the **principles of risk governance**. If risk tolerance and risk ownership are clear, science can contribute more easily with appropriate methods and appropriate thresholds for acceptable risks.

- There are two key challenges for the public sector: (1) obtaining timely advice during emergency management and (2) obtaining reliable advice for policy making. Both rely on **well-defined and sustainable science-policy interfaces** drawing from the best expertise available. Communication among the communities is particularly challenging, and should not be biased by skewed power relations.

- Participation of policy makers in existing partnerships should be encouraged. These include knowledge centres, alliances of research institutes, national DRR platforms, Community of Users, etc.

Knowledge

- More knowledge is needed on **integrated policy making** in the area of disaster risk reduction. A clear understanding of related policies, but also of legal, scientific and ethical aspects is required. Policy makers must both implement and shape regional and global frameworks (Sendai).

- The scientific community must **summarize and translate science** into policy language. The policy community must formulate long-term research challenges for the R&D community. This can help prioritize research funding.

Innovation

- **New approaches to risk governance must be tested**, including early warning and emergency management. The balance between national and European/regional systems must be optimized continuously, seeking to optimize cost-benefit, quality and effectiveness.

- A key challenge is to evaluate the (long-term) impact of science-based policies. There is a need for **quantifying the economic, social and humanitarian gains** of better incorporating science.

- New ways of **prioritizing research funding** should be sought based on proven needs of policy makers.

PRACTITIONERS

Partnership

- A key challenge for disaster risk reduction is to apply **global solutions to local problems**. Partnerships between scientists and practitioners can enable transfer of knowledge and practice necessary to implement available solutions. Scientists should be aware of the wide variety of social, legal, linguistic, physical and political contexts in which disaster risk management is practiced.

- Where possible, **trans-border agreements** should be put in place in advance, to foster joint exercise and prepare to face the real events. Such mechanisms can lead to harmonisation in preparedness and response planning.

- Preparedness planning should be comprehensive and involve multi-agency partnerships in order to make the transition from disaster management to risk management. The process should involve **collective action** by scientists, government, essential services, businesses, the media, other public, private and voluntary organisations and communities to help mitigate potential impacts. **Effective communication of risk**, considering power relations among actors, is an important challenge for scientists.

- **Existing Public Private Partnerships** and **Public Public Partnerships** show clear benefits in terms of efficient risk-sharing. Virtuous feedback loops lead to increased insurance coverage and penetration, investments in disaster risk reduction and innovative risk financing.

Knowledge

- Further research in **crisis management** is essential for practitioners. Developing new technology and infrastructure and improved models for **sense-making** of chaotic situations is necessary to allocate scarce resources more effectively during a crisis.

- Development or implementation of **standards** (e.g. on data formats or protocols, such as the CAP protocol, but also on hazard and risk assessment methods) can improve interoperability of the crisis management actors. Scientists, practitioners and policy makers must collaborate to develop practical standards.

- Understanding of **direct and indirect costs** is crucial to selecting and investing in preventive measures, as well the stakeholders to be involved, their roles and responsibilities. The private financial sector plays an important role, along with governments and civil society organizations, in designing innovative financial protection goals and sharing knowledge and capacity.

- The opportunities and challenges that the crisis information systems and social media brings to development of disaster risk management foster a process that builds principles for action for communities of practice, creating a '**space of meaning**' with theories for action, social change and instruments for implementation.

Innovation

- **Training, exercises and education** are essential to transfer scientific knowledge to practitioners.

- The **Internet of Things** is expected to provide citizens and emergency authorities with information and knowledge in real time. This will allow for new tools to be developed for a more resilient society. A balance needs to be struck between surveillance and privacy concerns.

- It is necessary to develop well-trained **downstream components** in early warning systems, incorporate volunteered geographical information.

- Rather than generating innovative approaches, **embedding and diffusion of innovations** is the key area that both policy and practice must address. Strong bonds and trust within and between communities favours a more effective response in emergencies and can be harnessed by authorities. Social media can also be used to enhance self-organised mobilisation and coordination of local resources, knowledge, and efforts for disaster preparedness and response.

Conclusions for European research

The EU and in particular its successive Research Framework Programmes (FPs) have actively supported various scientific research projects that, step by step, have contributed to a better understanding of risks in all their dimensions. Multinational and interdisciplinary research in the field of natural and technological disasters has led to the development of innovative tools and methodologies to forecast and monitor natural and human-induced hazards. In addition, research efforts in support of risk and crisis management have largely contributed to the preparedness for, and the response to, major crises and therefore helped reduce the toll on human lives and economic assets.

Since the 7th Framework Programme and now Horizon 2020, the EU research has become more multidisciplinary and has promoted a systemic-risk approach. The report highlights how research projects have been instrumental in delivering a deeper insight into the complex interactions between the hazard element and the natural and the built environment. New research avenues will further address the multi-risk impacts of physical hazards (floods, droughts, forest fires, etc) and the cascading effects of those hazards in order to integrate this information into the overall assessments.

EU-funded demonstration projects and other instruments (e.g., Public-Private Partnerships) are supporting the development and the awareness of risk mitigation and adaptation approaches (e.g. ecosystem-based Disaster Risk Reduction), as well as demonstrating their added value in terms of co-benefits for local economies, social cohesion and the broader environment. One of the priorities of the EU Action Plan for Disaster Risk Reduction is to foster green growth through promoting risk-proofed investments and building the capacity of local and national authorities and communities. Solution-driven research should help to explore how best to transform evolving challenges and problems into new opportunities and potential markets. Climate services, nature-based solutions for more resilient cities or territories and dynamic Earth observation are examples of promising sectors. A strong evidence base on the damage caused by disasters, the benefits of adaptation and mitigation measures, and the costs of inaction constitute key information that supports the science-policy interface and provides planners, designers, engineers and decision makers with appropriate tools for risk management.

Conclusions for UNISDR Science and Technology Roadmap

In response to a strong call in the Sendai Framework to "enhance the scientific and technical work on disaster risk reduction" (25(g)), the science and technology community, as well as other stakeholders, came together at the UN Office for Disaster Risk Reduction (UNISDR) Science and Technology Conference held 27- 29 January 2016 in Geneva. The conference produced a "Science and Technology Roadmap to Support the Implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030", which includes expected scientific outcomes, actions, and deliverables under each of the four priority of actions of the Sendai Framework.

This report is a contribution to the Science and Technology Roadmap, and specifically addresses, from a European perspective, topic 1.1 "Assess and update the current state of data, scientific and local and indigenous knowledge and technical expertise availability on disaster risks reduction and fill the gaps with new knowledge."

ANNEXES

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